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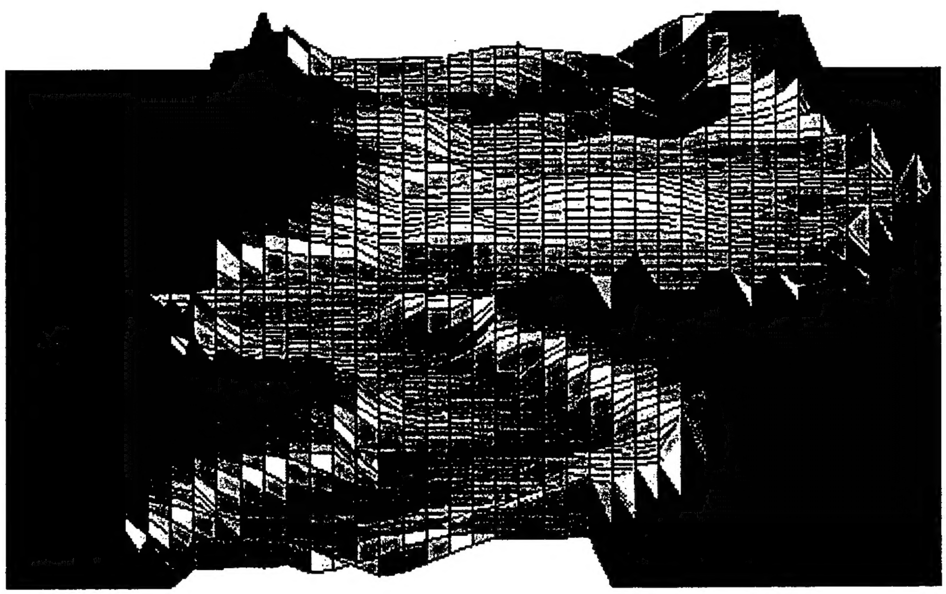
SERDP Project CS-1130

Dynamic Modeling of Landscape Evolution and Archaeological Site Distributions: A Three-Dimensional Approach

Meander-belt Topography



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The Department of Defense and the Department of Energy are stewards of millions of acres of land and the cultural resources they contain. Federal regulations require that DoD and DoE installations and facilities accomplish their respective missions in compliance with cultural resource laws. Compliance with Executive Order 11593, as codified in amendments to the National Historic Preservation Act of 1966 (NHPA), requires complete inventories of all historic properties on federally controlled lands. Additional legislation expands the compliance and stewardship roles of DoD and DoE in regard to historic preservation. These acts include the Archaeological Resources Protection Act (ARPA), the National Environmental Policy Act (NEPA), the Native American Graves Protection and Repatriation Act (NAGPRA), the American Indian Religious Freedom Act (AIRFA), and related Federal legislation.

Because of the protection from commercial exploitation, DoD- and DoE-administered lands (both cantonment and training/testing areas) contain some of the nation's most significant prehistoric archeological sites (e.g., the Yuchi Town village site at Fort Benning, GA; the Pendejo Cave site at Fort Bliss, NM; the Santa Elena site at the Marine Corps Recruit Depot, Parris Island, SC), as well as Native American and Native Hawaiian sacred sites and Traditional Cultural Properties (TCPs). At many Army installations across the nation, cantonment areas are known to contain nationally significant archeological sites associated with the history of the military. Historic preservation legislation and Army regulations require complete inventories and significance evaluations of all historic

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Dynamic Modeling of Landscape Evolution and Archaeological Site Distributions: A Three-Dimensional Approach

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Managing Buried Archaeological Sites on Military Training Lands

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Introduction

This document was prepared in fulfillment of Strategic Environmental Research and Development Program's (SERDP) "seed" project CS-1130, entitled *Dynamic Modeling of Landscape Evolution and Archaeological Site Distributions: A Three-Dimensional Approach.* It was conceived as a one-year "proof-of-concept" project within SERDP's Conservation Program. Performers include researchers from the Department of Defense (US Army Engineer Research and Development Center, CERL campus, Champaign, Illinois), the Department of Energy (Los Alamos National Laboratory), and academia (Massachusetts Institute of Technology and the University of Kansas). Although the Principal Investigator (Zeidler) was employed by the U.S. Army Engineer Research and Development Center in Champaign at the time of the project award, he has since moved to academia and serves as Associate Director for Cultural Resources in the Center for Environmental Management of Military Lands at Colorado State University, Fort Collins, Colorado. The original SERDP proposal on which this research was addressed the first part of SERDP Statement-of-Need No. CSSON-99-01 (SERDP 1997). This SON objective is as follows:

> *Provide the ability to effectively model and predict the distribution of archaeological (including prehistoric, historic, and traditional cultural property) resources on military and DoE lands and ranges, and address the potential or probability of unique impacts that adversely affect those resources.*

The remainder of this chapter is divided into six sections. The first section provides general background information on the legislative drivers and current fiscal situation that generated the methods proposed in this document, as well as the specific scientific rationale for developing a three-dimensional approach to the archaeological record. A recent example of an inadvertent discovery on Federal lands is then provided to illustrate the risks to mission currently faced by large Federal land-managing agencies in the area of archaeological resource management. The following four sections address specific issues raised by the SERDP Scientific Advisory Board. These include the projected Return-on-Investment or "value-added" component of the three-dimensional approach, the nature and effectiveness of the 3-D modeling effort, model validation procedures for subsurface site predictions, and the quantification of uncertainty.

A Rationale for Three-Dimensional Predictive Modeling and Risk Assessment of Archaeological Resources

The Department of Defense and the Department of Energy are stewards of millions of acres of land and the cultural resources they contain. Federal regulations require that DoD and DoE installations and facilities accomplish their respective missions in compliance with cultural resource laws. Compliance with Executive Order 11593, as codified in amendments to the National Historic Preservation Act of 1966 (NHPA), requires complete inventories of all historic properties on federally controlled lands. Additional legislation expands the compliance and stewardship roles of the DoD and DoE in regard to historic preservation. These acts include the Archaeological Resources Protection Act (ARPA), the National Environmental Policy Act (NEPA), the Native American Graves Protection and Repatriation Act (NAGPRA), the American Indian Religious Freedom Act (AIRFA), and related Federal legislation.

Because of the protection from commercial exploitation, DoD- and DoE-administered lands (both cantonment and training/testing areas) contain some of the nation's most significant prehistoric archeological sites (e.g., the Yuchi Town village site at Fort Benning, GA; the Pendejo Cave site at Fort Bliss, NM; the Santa Elena site at the Marine Corps Recruit Depot, Parris Island, SC), as well as Native American and Native Hawaiian sacred sites and Traditional Cultural Properties (TCPs). At many Army installations across the nation, cantonment areas are known to contain nationally significant archeological sites associated with the history of the military. Historic preservation legislation and Army regulations require complete inventories and significance evaluations of all historic properties on Federally owned or administered lands.

In accordance with legislative mandates, the DoD had a Measure of Merit to identify and evaluate all cultural resources by the year 2000, a goal that was difficult if not impossible to achieve. For archaeological resources, traditional methods of identification imply systematic, labor-intensive, walk-overs by closely spaced field crews during which the modern ground surface is visually inspected for traces of prehistoric or historic cultural artifacts or features. Where dense vegetation obscures the ground surface, systematic shovel-probe are often excavated at fixed intervals and uniform depths (e.g., 50 cm), and the fill is routinely screened for cultural materials. Once a site is discovered, a separate testing and evaluation phase is sometimes required to determine the site's significance and potential eligibility for listing on the Nation Register of Historic Places. This generally involves systematic surface collecting and close interval shovel-probing of the site, followed by careful hand excavation of a series of small (ca. 1 x 1 m or 1 x 2 m) test pits. It is estimated that together the DoD and DoE currently have over 27 million acres of land. Only 30% of this acreage has been systematically surveyed for archaeological resources, leaving some 18.9 million acres unsurveyed. At today's cost of $35-45 per acre for standard survey, this goal is both cost-prohibitive and temporally impossible, as it would require an expenditure of between $661-850M over the next two years. Even relaxing the time requirement would not alleviate the overwhelming cost burden. Therefore, innovative and cost-effective ways of addressing these requirements must be developed.

We argue that by developing a three-dimensional risk-based approach to predictive archaeological modeling and inventory survey methods, the DoD and DoE can substantially

reduce the amount of acreage requiring survey and reduce the costs associated with surveying by eliminating from consideration landforms of inappropriate age or landforms so disturbed either from natural or anthropogenic processes that they are extremely unlikely to contain intact archaeological sites. In these cases, the Federal agency can seek concurrence from the State Historic Preservation Office for purposes of exempting such lands from systematic archaeological survey under the law. The remaining lands can then be efficiently managed by prioritizing the landscape in terms of relative archaeological resource potential and relative risk of impact.

Although archaeological survey is expensive, it is only the first step in the cultural resource evaluation process. Once archaeological surveys have been completed, newly discovered sites must be evaluated for "significance" and eligibility for inclusion on the National Register of Historic Places (NRHP). Until eligibility assessments are completed, *all* sites are considered eligible and are afforded full protection under the NHPA. Current practices are inefficient in that they view the inventory and evaluation process as a linear progression from field survey to eligibility assessment to protection, where all lands are first surveyed, then all the discovered sites are evaluated, etc. A more efficient and cost-effective approach would be to begin by *prioritizing* sites according to (a) their potential impacts from modern land use (risk) and (b) their potential to contain intact archaeological resources based on predictive modeling. The qualifying term *intact* is significant since NRHP criteria place a strong emphasis on site integrity for eligibility assessments, and geomorphic processes and stratigraphic context are important criteria for deciding which lands will contain *significant* resources (i.e., NRHP-eligible). Heavily eroded or disturbed landscapes, in most cases, can be excluded from survey, since they have a low potential for containing intact archaeological sites. Those areas that are experiencing heavy modern impacts and have a high potential to contain intact archaeological resources should be given highest priority for survey and site assessment. Those lands that are heavily impacted but have little potential for intact archaeological resources would fall into the second tier of priority. Accordingly, those areas that have a high potential for cultural resources, but are experiencing no land-use impacts would fall into a third tier of priority, and those areas that are not impacted and have a low potential for archaeological resources would be given the lowest priority for survey.

We argue that high priority lands should be surveyed and any discovered sites evaluated *as a single process* so that the DoD and DoE can avoid two common problems that have historically impacted the use of military training and testing lands. First, in some instances large tracts of training land have been surveyed over the course of many years, while no site evaluations have taken place. As a result of this strategy, a large number of sites must be protected until evaluation can take place, thus reducing or constraining the use of these lands for training. The majority of these sites will not meet the NRHP criteria for eligibility and should not require protection, but until the evaluations are made, these sites must be protected. The second problem is encountered when there is a large backlog of sites requiring evaluation and no means to prioritize which sites should be evaluated first.

Given the high and ever-increasing costs of archaeological inventory survey, the approach to survey should be to first evaluate those sites and potential resources which create the

greatest risk to mission by reducing the DoD and DoE ability to use the land for training and testing. These high risk areas are significantly less than the total acreage needing survey under the law. The research approach proposed herein will significantly reduce the acreage requiring survey and the number of sites requiring assessment, yet still fulfill the spirit and intent of Federal historic preservation legislation.

Approaching the Third Dimension: Buried Archaeological Sites and Inadvertent Discoveries

While the risk-based strategy outlined above for landscape prioritization is an effective means of reducing the surface acreage of archaeological inventory surveys, it is only a partial solution to the problems encountered by cultural resource managers on Federal lands. Traditional two-dimensional predictive modeling capabilities (i.e., those based solely on surface archaeological site distributions) can effectively remove from consideration land parcels that have little or no archeological potential on the surface. However, it is important to emphasize that surficial archeological sites represent only a *fraction* of the sites that may be present in a given landscape. Moreover, the distribution of surface and near-surface sites often differs from that of (often more valuable) buried sites, due to the land altering effects of different geomorphological processes such as erosion and deposition. Erosional processes may destroy archeological sites or redeposit them in stratigraphic contexts different from those in which the originated, while depositional processes may leave sites buried in their original stratigraphic context but invisible on the modern surface. *The potential presence of buried archaeological sites represents a formidable risk to land managers, since inadvertent discoveries resulting from military-unique training and testing activities can generate costly delays for stakeholder consultation, legal actions, and/or resource mitigation.* This holds true especially with respect to alluvial floodplain environments (Brown 1996; Holliday 1992; Howard and Macklin 1999; Gardner and Donahue 1985; Gladfelter 1985; and Kraus and Brown 1986; Tucker et al. 1999a; Waters and Kuehn 1996), but as we shall see below, can also be a concern in upland aeolian environments as well.

With continued base closures and troop realignments, military training and infrastructure requirements necessitate flexible and less constrained use of training lands. Accidental finds of buried archeological sites through military-unique activities, especially if they contain Native American human remains, require that the Federal agency immediately halt all activities affecting the resource. This process can result in fragmentation of training lands and construction sites, and represents an unacceptable loss of time and money in an already stressed training/testing budget. It also represents an unacceptable loss of *non-renewable* archaeological resources, if these resources are deemed significant and eligible for listing on the National Register of Historic Places (NRHP) under the terms of the National Historic Preservation Act (NHPA). Therefore, an "archeological sensitivity map" describing the potential location of artifact-bearing strata in relation to the modern soil surface is an indispensable tool for cultural resource managers. These modeling approaches will increase in utility and importance through time, as budgetary constraints require land managers to rely more heavily on model-based decision support tools.

It is well known that routine military training can have dramatic cumulative impacts on the landscape. According to one recent study based on Land Condition Trend Analysis (LCTA) data, 58% of LCTA plots on Army training lands "exhibit some type of military land use. The most severe military impacts are from tracked and wheeled vehicle maneuvers, resulting in compacted soil, crushed or destroyed vegetation, loss of ground cover, and ultimately the loss of soil through erosion" (Shaw and Kowalski 1996:2-3). Of the 58% of plots showing some type of military land use, approximately 60% exhibit wheeled-vehicle use, while half of them have tracked-vehicle use. The subsurface nature of these military-unique impacts (especially severe soil erosion) and their potential effects on the archaeological record have received very little analytical attention (Figure 1.1). Training use distribution modeling based on installation-wide LCTA data is largely focused on *surficial disturbance* from tracked and wheeled tactical vehicles (Guertin et al. 1998). U.S. Army maneuver damage assessments are based on specific training episodes and generally consider impacts up to 30 cm. deep (12 in.) from vehicle ruts and their implications for soil erosion (see for example Pearson et al. 1990). Other studies have examined mechanized maneuver impacts or foot traffic impacts to vegetation and soil (see Milchunas et al. 1999; Milchunas et al. 2000; Prosser et al. 2000; and Whitecotton et al. 2000 for recent examples), but again they are largely confined to the land surface. These kinds of studies are important tools for the cultural resource manager and have been carried out at several Army installations having intensive training missions. However, impacts exceeding the top 20 to 30 cm. of the landscape have not been given systematic consideration, so the potential effects and spatial scale of deep impacts on the archaeological record are difficult to assess (see below). Even in cases where the magnitude of the disturbance from combat-related mechanized digging is acknowledged, the fact that Army regulations require routine back-filling of these excavations obviates most of the concern for this type of disturbance regime (see, for example, Demarais et al. 1999). Even so, such excavations can have a devastating impact on buried archaeological resources that are, by definition, *non-renewable*.

Archaeological site monitoring studies at two Army installations have afforded some idea of the nature of military training impacts to limited numbers of sites (see, for example, Briuer and Niquette [1983]; Carlson and Briuer [1986]; and Richardson and Hargrave [1997]). These studies have been primarily concerned with documentation of surface damage, but Richardson and Hargrave (1997) also demonstrate the potentially deep impacts created by military training excavations conducted either by individual troops or by mechanized Combat Engineers for concealment purposes (Figure 1.2). Table 1.1 shows the dimensions stipulated by training doctrine for a wide range of concealment excavations ranging from M1 tanks to individual fighting positions (Department of the Army 1985). The volume of soil represented by many of these excavations is impressive (often extending well below 2 meters in depth), especially when considering that they apply to a single vehicle! When considered from the perspective of multiple excavations for a single training scenario, the three-dimensional footprint of this digging activity is staggering. Very little data exists, however, on the potential impacts of such activities on the subsurface archaeological record. Likewise, the potential of such activities to encounter an inadvertent archaeological find cannot be ascertained *unless concrete prior information exists on archaeological sensitivity*.

Table 1. Dimensions of Military Training Excavations*

Vehicle/Equipment Type	Hull Defilade				Turret Defilade				Position Type
	Length (m)	Width (m)	Depth (m)	Volume (m3)	Length (m)	Width (m)	Depth (m)	Volume (m3)	
M1 battle tank	10.00	5.50	2.00	110.00	10.00	5.00	3.00	150.00	Deliberate
M60/M48 battle tank	9.50	5.50	2.00	104.50	9.50	5.00	3.00	142.50	Deliberate
M2 and M3 fighting vehicle	8.00	5.00	2.50	100.00	8.00	5.00	3.00	120.00	Deliberate
M901 TOW vehicle	7.00	4.50	2.00	63.00	7.00	4.50	3.00	94.50	Deliberate
M113 series carrier	7.00	4.50	2.00	63.00					Hasty
M577command post vehicle	7.00	4.50	3.00	94.50					Hasty
M106, M125 mortar carrier	7.00	5.00	2.50	87.50					Hasty
Chaparral (M730)	7.80	4.50	1.20	42.10					Deliberate
Hawk	7.80	4.50	1.20	42.10					Deliberate
General support rocket launcher	8.00	5.10	0.90	36.70					Deliberate
155-mm howitzer	32.00	5.40	1.50	259.20					Deliberate
8-in howitzer	32.40	5.00	1.50	243.00					Deliberate
175-mm M107 gun	31.50	4.80	1.50	226.00					Deliberate
.25-ton truck (CUCV)	5.40	3.60	2.10	40.80					Deep-cut
1.25-ton truck (HUMMV)	6.00	3.90	2.70	63.10					Deep-cut
2.25-ton cargo truck	8.70	3.90	3.00	101.80					Deep-cut
2.25-ton shop van	8.40	4.20	3.60	127.00					Deep-cut
5-ton cargo truck	11.40	4.20	3.00	143.60					Deep-cut
10-ton cargo truck	10.20	4.80	3.60	176.30					Deep-cut
10-ton trailer w/ van semi-trailer	15.90	4.80	2.90	221.30					Deep-cut
81-mm mortar	1.80	0.90	0.90	1.50					Hasty
4.2-in mortar	2.40	0.90	0.90	1.90					Hasty
One-soldier fighting position	0.90	0.60	0.75	0.40					Deliberate
Two-soldier fighting position	1.80	0.75	1.37	1.90					Deliberate
Prone position	body	0.75	0.46	?					Hasty
Machine gun position	1.67	1.80	1.37	4.10					Deliberate
Anti-tank ditch	3.30	?	1.50	?					Deliberate

* SOURCE: Department of the Army (1985) *Survivability*. Field Manual No. 5-103. Washington, DC.

The inability to accurately predict the location of buried archeological sites, sites that are responsible for the majority of inadvertent discoveries, results from the inability to accurately model the geomorphic processes which have shaped the present landscape. The peopling of the New World extends back at least 12,000 years and arguably as far back as 20,000 years before present. Landscape alteration resulting from global climatic changes during, and at the end of the Pleistocene (i.e., the last Ice Age), has caused changes in human settlement patterns and consequently the distribution of archeological sites and their visibility. Holocene landscape evolution (beginning ca. 10,000 years ago) has continued to the present, in some cases obscuring the archeological record. Presently, predictive archeological models have approached this problem two-dimensionally by collapsing the archeological record into a single, atemporal model that expresses the distribution of sites as a single surface. However, *the archeological record exists in three-dimensional space* and must be understood within a spatial and temporal geomorphic context. The probability of finding cultural material on the surface is generally not the same as finding it at a depth of 1 meter, nor is the risk of disturbing cultural materials at 1 meter below surface the same as the risk to materials lying 2 meters below the surface. In addition, the value of cultural materials sometimes increases with their age (due to their rarity), which is usually (though not always) correlated with burial depth. By examining the landscape three-dimensionally, areas of potential site destruction, as well as areas of potential site preservation can be identified. These kinds of data have the potential to effectively remove significant tracts of land from archeological consideration, thus focusing scarce management dollars on those parts of the installation having optimal preservation contexts for archeological resources.

This problem has two correlates: (1) the lack of archaeological field strategies directed at recovering under-represented, buried archeological sites based on landscape evolution modeling; and (2) the lack of archaeological field strategies to assess "archeological sensitivity"--the proximity of buried archaeological sites to the present soil surface. To address these problems adequately, predictive models must have a temporal and three-dimensional spatial emphasis. In this sense, the vertical axis becomes not only a surrogate for site age, but also an index of archeological sensitivity. However, for this strategy to be successful, simulation models must have some measure of predictive capability. An assessment of the capability of landscape evolution simulations to realistically model the landscape is an important objective of this research thrust.

Inadvertent Discoveries and Risk to Mission: A Recent DoE Example

The potential risk to the DoD/DoE mission caused by inadvertent discoveries of buried archaeological resources can be illustrated by a recent case of a proposed expansion to a security perimeter on a large DoE facility in the western U.S. The proposed undertaking was halted because of the inadvertent discovery of prehistoric Native American human remains and associated cultural objects dating to approximately A.D. 1150-1325. The burial was exposed at approximately one meter below the modern surface within the footprint of the proposed project. Prior to this chance find, no project delays were anticipated due to cultural resource issues, since the area in question had been previously surveyed by traditional archaeological survey methods and no surface archaeological remains had been detected. Since several Native American groups

living in close proximity to the facility consider this discovery to be a "sacred" cultural property, it has generated a considerable amount of local stakeholder interest and concern with respect to the Native American Graves Protection and Repatriation Act (NAGPRA) and the American Indian Religious Freedom Act (AIRFA). In accordance with those legislative requirements, all construction activities at the site had to be halted for the mandatory consultation period and it has taken 5 months thus far to even initiate the consultation process. The DoE Cultural Resource personnel expect the ensuing Native American consultation process to occupy several additional months during which the proposed construction cannot proceed. Further delays could occur should the consultation process result in stakeholder litigation. From the perspective of the Federal land-managing agency, this is an unacceptable yet now unavoidable loss of time and money. At the same time, however, Native American claims of Federal insensitivity to their religious rights continue to increase across the United States[1] and cultural resource managers must pay particular attention to the potential for inadvertent discoveries and ensuing litigation. In this DoE example, the chance find is one of potentially hundreds of Native American burials that may exist below the surface, and there is currently no reliable way of predicting their location.

We argue that these kinds of costly inadvertent discoveries could be anticipated if a three-dimensional approach to the initial archaeological inventory survey were adopted. More specifically, detailed geomorphological testing and mapping on a landscape scale would likely have alerted the cultural resource managers to the *potential* existence of buried archaeological sites within the landform(s) in question. At a minimum, such knowledge would then permit the responsible cultural resource manager to make an informed "go/no-go" decision regarding the proposed Federal undertaking. This could involve a decision to avoid the area entirely or a decision to conduct very limited subsurface testing to determine the actual presence of archaeological resources prior to issuing a clearance for undertakings on that land. While geomorphic mapping and subsurface sampling may seem like a costly method to pursue in this case, it is far cheaper than the cost of finding an inadvertent discovery and the potential litigation and costly delays or stoppage that such a find can engender.

The Nature and Limitations of 2D Approaches to Predictive Modeling and Archaeological Inventory Survey at Fort Riley, Kansas

The limitations of two-dimensional approaches to archaeological inventory survey and predictive archaeological modeling can be illustrated through recent work at Fort Riley, Kansas. Figure 1.3 shows a 2D predictive archaeological model of the installation and Figure 1.4 illustrates the archaeological survey areas and site distributions used for model development. The predictive model was developed using a split sampling procedure where one-half of the site sample was employed for model development and the other half for model validation. While the model is an effective decision tool with respect to the "surface" archaeological record, it is not an accurate predictor of buried archaeological resources in that it over-generalizes the nature of archaeological sensitivity. For example, the upland zones generally fall in the lowest probability category for archaeological resource potential, yet deep geomorphic testing (Figure 1.5) has revealed buried remains at several upland localities sampled. In a similar fashion, alluvial areas generally fall in the highest probability category for archaeological resource potential, yet deep geomorphic testing and landform mapping has shown that this is not uniformly the case.

Different landforms within the floodplain have different archaeological sensitivities depending on their particular depositional history. Thus in both upland and alluvial contexts, a two-dimensional approach does not adequately address the potential for buried archaeological resources.

Figure 1.6 shows a portion of the Upper Wildcat Creek drainage, located in the northeastern sector of the installation, where traditional archaeological survey has recently been conducted (Survey Tracts A, B, C1-C10, J, I, and 315. This involved close-interval pedestrian inspection of the ground surface supplemented by shovel-testing in areas of dense vegetation (<20% visibility). Subsurface testing is thus guided by presence or absence of vegetation rather than the presence of specific landforms and probe depth is limited to 50 cm in most cases. Current methods are inefficient in that the methodological rigor employed for surface inspection or for subsurface testing is not adjusted for the particular landform(s) under study. Field methods may be more rigorous than necessary for certain landforms, resulting in misspent time and money, or they may not be rigorous enough, resulting in a still considerable level-of-effort expended with little or no return on site discovery or gain in archaeological knowledge. Prior geoarchaeological modeling would permit tailoring the survey strategies to the different landforms of a study area, thereby eliminating the costly and inefficient "one-size-fits-all" approach commonly practiced today.

The 3-D Modeling Effort in Archaeological Perspective

Technical Objectives

This research is focused on providing the theoretical and methodological basis for the development and implementation of new tools necessary for more accurate modeling of dynamic landscape processes and the formation of the archaeological record. The general objective is to increase the realism of simulation modeling for application to archeological site prediction in three dimensions to enhance model-based decision support in cultural resource management. What is lacking in the site discovery process is a reliable method to generalize from point data the distribution of promising locations for site distribution on a landscape scale. This research addresses that needed capability and will demonstrate its effectiveness in a concrete case study at the Fort Riley Military Reservation.

The SERDP "seed" project had the following four technical objectives: (1) collect a 3D archaeological and paleoenvironmental data set at Fort Riley; (2) use geomorphic simulation modeling to develop a rational, quantitative basis for inferring the relationship between landforms and archaeological preservation potential; (3) test the geomorphic modeling using archaeological and geomorphological survey data; and (4) use the results from the above to generate maps of archaeological resource potential as a function of age and depth.

The three-dimensional approach outlined above has been employed at Fort Riley for purposes of overcoming current limitations in predictive archaeological modeling and Training Use Distribution modeling, both of which are based solely on a two-dimensional or surficial assessment of the landscape. This will be accomplished through the development of an

"archaeological sensitivity map" which will plot the potential distribution of *buried archaeological sites* and their likely proximity to the modern ground surface. These results can then be utilized in two different but related ways. First, the subsurface "archaeological sensitivity map" can be compared to the 2-D predictive model showing the probabilities of finding surface archaeological sites. Areas of coincidence as well as areas of discrepancy between the two distributions can be identified spatially and the 3-D sensitivity map can then be used as an amendment or complement to the 2-D predictive model for purposes of CRM decision-making. Second, the "archaeological sensitivity map" can be assessed with respect to depth-of-impact data to be gathered on military maneuver damage at Fort Riley. This will provide a third dimension to the 2-D training use distribution model currently available for the Fort Riley landscape and permit assessment of the potential impacts on military training, testing, and construction activities on BOTH the surface and subsurface archaeological record.

No archaeological risk assessment can be complete until the Holocene archaeological record is considered in its entirety. Likewise, archaeological inventory surveys will remain inefficient and costly until field methods are guided by a three-dimensional approach to the archaeological record and until the selection of site discovery techniques is tailored to specific landforms making up the study area.

Model Validation

Model validation procedures in two-dimensional predictive modeling efforts are typically carried out in two ways, and usually in a sequence. The first validation is generally carried out as part of the same modeling exercise using split-sampling techniques. Ideally, the sample of archaeological sites is large enough to split in half in a random manner. The first half is then used to develop the model (i.e., a training sample) and the second half is used to validate the model upon completion (i.e., the validation or test sample). In this way, validation is conducted independently of model development, although the two split samples are derived from the same set(s) of original field data. If the validation sample demonstrates a sufficiently high percentage of correct predictions based on a pre-determined model performance threshold (say, 75% or higher), then the model can legitimately be considered valid for use in cultural resource management decision-making.[2] At a future date, it may be prudent to conduct additional validation exercises using completely independent data sets gathered through new archaeological field surveys that are routinely carried out as part of the installation compliance obligation. If the newly discovered sites from these surveys match or improve upon the percent-correct predictions of the model, then even more confidence can be placed on the original model. Such gains (or losses) in predictive accuracy can be quantified through significance testing and the calculation of confidence intervals around the percent-correct (or percent-incorrect) predictions. These routine statistical procedures readily facilitate comparisons between model validation exercises as well as between different models employing the same data set.

For the three-dimensional case of predictive modeling, model validation must generally follow a different procedure simply because the sample of known buried archaeological sites is usually quite small compared to those recorded through surface survey. Thus, split-sampling procedures are not an option and the limited number of buried sites must be used to estimate the

potential for other buried sites across the landscape based on similarities in the geomorphological context of the known sites (i.e., their chronostratigraphic placement within similar landforms or alloformations). At Fort Riley, for example, the limited subsurface testing (backhoe trenching, coring, and profiling of existing vertical exposures) that has been carried out indicates a fairly high potential for buried archaeological sites in several of the sampled landforms. For example, of the 49 backhoe trenches excavated, 14 (28%) revealed evidence of *buried* prehistoric cultural remains (hearths, debitage, midden, etc.). Of the 17 channel cutbanks that were profiled, 7 (41%) revealed such evidence. Finally, of the more than 100 small-diameter cores that were extracted, some 5% of them yielded evidence of cultural remains (lithic debitage or possible hearth/midden deposits). These figures indicate a rather rich *buried archaeological assemblage* at Fort Riley and reinforce our contention that the surface distribution of archaeological sites represents only a fraction of the total archaeological record. Even so, the overall number of subsurface prehistoric sites revealed in these limited sub-surface testing operations (ca. 25 sites) falls well below that identified through years of surface survey (ca. 210 prehistoric sites) and is far too small a sample to employ split-sampling procedures and multivariate statistical analysis.

In this case, then, model validation must be carried out through future archaeological survey involving subsurface testing. It is important to point out, however, that validation does not require massive excavation of the subsurface, but only judicious subsurface sampling using coring devices and perhaps limited backhoe trenching. Such future sampling procedures should be carried out in previously unsurveyed areas and should focus on geomorphic landforms and chronostratigraphic contexts judged to be similar to those defined in the initial geomorphic study. If the 3-D model is valid, then these newly sampled landforms should reveal subsurface cultural deposits in quantities approximately similar to those recovered in the initial sampling, as outlined above.

Critics of such an approach might object by saying that if a given Federal undertaking requires digging into the subsurface anyway (e.g., for construction activities, for road-building, for vehicle concealment, etc.), then why not wait until the undertaking is in progress to determine if subsurface archaeological remains are present and not waste the extra funds needed for 3-D geomorphological investigation and model validation? We view this approach as both risky and short-sighted, as it exposes the agency to the possibility of encountering *unanticipated* archaeological resources, and the entire undertaking would then run the risk of being shut down or at least delayed. In our view, this represents an unacceptable loss of time and money, especially in cases where detailed and lengthy planning is required to execute the undertaking (e.g., a large-scale military training exercise). Geomorphic modeling and validation through subsurface sampling is always preferable to after-the-fact "validation" through inadvertent discovery *during* a Federal undertaking. By taking a proactive stance on the potential for buried archaeological sites and formally defining areas of the landscape that are likely to contain such resources, CRM personnel can advise installation planners of this risk *prior* to initiating undertakings in these areas.

Quantification of Uncertainty

The quantification of uncertainty in the three-dimensional predictive modeling approach is addressed somewhat differently than that attainable through two-dimensional modeling. In the latter case, multivariate statistical procedures can be applied to a reasonably large sample of known archaeological site locations and the output is expressed as a 'probability surface map" in which distinct numerical probabilities (e.g., 0 to 100%) are generated for given land parcels. The investigator can then group this output in a variety of ways to express discrete polygons over a GIS-based "surface". For example, in a recently completed 2-D predictive model generated for Fort Riley by the senior author, these probabilities were expressed quantitatively on a ratio scale of measurement using 6 groupings, as follows: 0-20% 21-50%, 51-70%, 71-80, 81-90%, and 91-100%. These groupings follow the recommendations of Warren (1990) for a comparable predictive modeling effort conducted in southern Illinois. This provide a very useful quantification of uncertainty or certainty for purposes of making managerial decisions or for prioritizing the landscape in terms of relative site potential. In some cases, however, the resource manager may only need a general rule-of-thumb to guide decision-making, in which case this six-fold grouping can be collapsed into three broader ordinal-scale groupings of low, medium, and high probability (e.g., 0-50% = low, 51-80% = medium, and 81-100 % = high).

In the case of the 3-D approach to predictive modeling, probabilities of the potential for buried archaeological sites cannot be expressed with the same level of precision found in the multivariate statistical analysis of the 2-D approach. In this case, the geomorphologist usually expresses these probabilities on a more qualitative basis by simply using an ordinal-scale grouping of high, moderate, and low potential (see, for example, Albertson et al. 1995). These judgements are based on previous examination of known buried sites on landforms of a given age. As mentioned in the previous section, the expectation that such sites are likely to be found on similar landforms in similar chronostratigraphic positions (i.e., allostratigraphic unit or alloformation) is simply extrapolated to the rest of the landscape under study. Ideally these expectations should be expressed in conjunction with an estimate of the depth at which buried sites might be found. As an example of this procedure, we can turn to Fort Leonard Wood, MO. In their geomorphic study of alluvial terraces at Fort Leonard Wood, Albertson et al. (1995:98-99) indicate that "the T3 Dundas [formation] with an age range of 2,000 to 3,000 years BP has moderate potential in the upper 50 cm but has high potential for buried sites to a depth of 2 m." The T4 Quesenberry and T5 Miller formations, on the other hand, show "high potential in the upper 50 cm and low to moderate potential to 1.5 and 1 m respectively" (Albertson et al. 1995:99). This information is then combined with a GIS-based map of these various landforms or alloformations on the surface, resulting in an "archaeological sensitivity map". Thus, while not as quantitatively precise at the probabilities expressed in 2-D predictive modeling, these qualitative expressions of buried site potential across the landscape are extremely useful for the installation cultural resource manager and for the field archaeologist. Both landscape-scale risk assessment and the development of detailed, cost-effective field survey methodologies are facilitated by having this kind of information. At Fort Leonard Wood, all Scopes-of-Work for contracted archaeological inventory surveys now routinely include detailed specifications regarding the kinds of archaeological inspection techniques and subsurface testing procedures that *must* be employed for the field inspection of specific landforms found in the study area.

These specifications take into account both the likelihood of finding buried sites as well as their estimated depth below the modern ground surface.

Return-on-Investment for the 3-D Approach

Calculating ROI for Archaeological Resources

The benefits of the three-dimensional approach to predictive archaeological modeling can be characterized in a risk-based framework in terms of three inter-related kinds of risk: (1) risk to fiscal resources; (2) risk to the military training and testing mission; and (3) risk to the archaeological resources. All three of these risk factors must be carefully balanced so that proactive legislative compliance and proper resource stewardship can be accomplished with minimal risk to the military mission. Risk to fiscal resources can occur if and when the military mission is put at risk through stoppage or delay of undertakings resulting from improper or inefficient compliance and stewardship procedures and/or unforeseen compliance issues such as an inadvertent discovery.

In this context, calculating the Return-on-Investment for the three-dimensional approach to predictive archaeological modeling must address two separate cost issues: (1) the cost of conducting archaeological inventory surveys using current standards and guidelines; and (2) the cost of finding an inadvertent discovery that results in activity stoppage or delay and costly litigation or fines. The 3-D approach advocated here is designed to minimize BOTH of these costs by means of a relatively modest investment in Holocene geomorphological modeling, analysis, and mapping on a landscape scale.

Cost Estimation

There are over 27 million acres of land under Department of Defense and Department of Energy jurisdiction (12 million acres of Army land alone). Approximately 30% of those lands have been systematically surveyed, leaving 18.9 million acres to be surveyed. At current prices ranging from \$35-45/acre for standard archaeological survey, the remaining lands will cost a staggering \$661M-850.5M to complete. By employing the proposed methods, this cost can be significantly reduced. Based on previous experience, we estimate that total acreage of the survey could be reduced by 35-40% using 3-dimensional predictive modeling to remove areas from consideration that have little or no potential for containing intact archaeological sites. This would result in potential cost savings ranging from \$ 231M to 382.7M, assuming that the goal of complete survey coverage is even attainable. Even at the individual installation level, however, the potential elimination of 35-40% of future survey acreage would represent a tremendous cost avoidance. Likewise, specific field methods for conducting survey (e.g., crew interval spacing, spacing and depth requirements for subsurface probes, etc.) could be tailored to the different landforms of a study area, thereby eliminating the costly and inefficient "one-size-fits-all" approach commonly practiced today. Current methods are inefficient in that the methodological rigor employed for surface inspection or for subsurface testing is not adjusted for the particular landform(s) under study. Field methods may be more rigorous than necessary, resulting in wasted time and money, or they may not be rigorous enough, resulting in a still considerable

level-of-effort expended with little or no return on site identification or gain in archaeological knowledge. For example, a landform known to have experienced significant deposition in the past 10,000 years could potentially contain deeply buried sites that would be missed by standard 50-cm deep shovel test pits placed at 10-meter intervals.

The second area where significant cost avoidance can be realized is in the potential delays and stoppages caused by inadvertent discoveries of archaeological sites, particularly those involving Native American human remains. The threat to the DoD/DoE training and testing mission posed by such on-the-spot discoveries and resulting litigation is not trivial, as the previous DoE example demonstrates. Such stoppages, temporary delays, or even modifications of planned training/testing scenarios can be potentially costly both in time and in money, often in the millions of dollars.

In our view, a relatively modest investment in geomorphological field work and analysis would provide the cultural resource manager with invaluable information for proactive and cost-effective resource management. First, it would permit the development of detailed scopes-of-work for matching appropriate survey methods and site discovery procedures to particular landforms. Second, and perhaps more importantly, this information would permit informed decisions regarding potential for buried archaeological sites and, hence, the risk of making inadvertent discoveries during a proposed undertaking such as training scenarios with subsurface impacts or construction activities that involve digging. Basic geomorphic mapping and the identification of subsurface zones of high potential for site preservation can be conducted at a current cost ranging from only $1-3 per acre. This figure is based on cost data from three Army installations in disparate physiographic and ecological settings (Fort Riley, KS, Fort Bliss, TX/NM, and Fort Leonard Wood, MO). Our approach to three-dimensional modeling would add on the cost of implementing the CHILD geomorphic process model (developed by the Department of Civil and Environmental Engineering, MIT) as a component of the reconstruction of landform evolution, and the cost of carrying out the three-dimensional risk assessment of military impacts on the archaeological record using the Training Use Distribution Modeling (developed by the Land Management Laboratory, USACERL). The net result of this approach for the DoD or DoE installation would be two-fold:

(1) a "smarter, faster, cheaper" approach to archaeological inventory survey mandated by federal legislation (NHPA, Section 110) for the identification of all archaeological resources; and
(2) a proactive and cost-effective method for avoiding potentially costly inadvertent discoveries of buried archaeological resources and Native American human remains.

We feel that this is the only reasonable and comprehensive approach to Part 1 of the SERDP Statement-of-Need CSSON-99-01, as outlined at the beginning of this chapter.

The following three chapters address, respectively, the following topics: (a) the most recent version of the Channel-Hillslope Integrated Landscape Development (CHILD) model and its application to the computer simulation of archaeological site formation and destruction in depositional geomorphic environments; (b) the most recent empirical geomorphological and geoarchaeological data from selected watersheds at Fort Riley, Kansas, that was used both to

calibrate aspects of the CHILD model and to validate the simulation results derived from the model predictions; and (c) information on the potential transferability of the CHILD model to Los Alamos National Laboratory, New Mexico for purposes of predicting the presence of buried archaeological sites at that Department of Energy facility. The report concludes with a brief summary on the potential benefits of the CHILD model for archaeological resource management on federal lands.

Notes

1 See Bray and Killion (1994), Echo-Hawk and Echo-Hawk (1994), Gulliford (2000), Mihesuah (2000), Swidler et al. (1997), and Vescey (1993) for representative literature on this issue. For specific discussion of the legal issues involved, see Bowman (1989), Harris (1991) and Hutt et al. (1999:291-392). See also Claiborne (2000) for another recent case of inadvertent discovery on lands managed by the U.S. Army Corps of Engineers.

2 It should be noted that the selection of a suitable model performance threshold is somewhat arbitrary and can vary among different archaeologists from as low as 65% (e.g., Warren 1990) to 85% (e.g., Kvamme 1992). Obviously, the higher the threshold is, the more accurate and reliable the model will be in correctly predicting site presence and site absence.

Chapter 2
Modeling the 3D Stratigraphic Context of Prehistoric Sites: A New Approach Using Process-Based Computer Simulation

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Introduction

An important step in developing predictive archaeological models is to establish a rational, quantitative basis for inferring the three-dimensional relationship between geomorphic properties and archaeological resource potential. Artifact burial depth and preservation potential are clearly a function of the geomorphic processes that have modified the landscape since the time of prehistoric habitation. Patterns of erosion and deposition in response to climate changes, such as those that have effected the Great Plains and the arid southwest during the period of prehistoric habitation, are known to vary systematically according to landscape position (Rinaldo et al. 1995; Tucker and Slingerland 1997; Tucker and Bras 1998). We propose to quantify the relationship between preservation potential, landscape position, and geomorphic history by using a distributed, process-based geomorphic model to simulate climate-driven erosion and deposition patterns. The Channel-Hillslope Integrated Landscape Development (CHILD) model, which simulates long-term landscape erosion and deposition, will be used for this purpose (Tucker et al. 1997). The CHILD model is the only model of its kind to incorporate the effects of varying storm duration and intensity, so that it provides a platform for analyzing the geomorphic impacts of Holocene changes in storm intensity over the mid-continent (e.g., Knox, 1983; Tucker et al., 1998). Predecessors of the model have already been used successfully to model patterns of landscape change in response to climatic fluctuation (e.g., Tucker and Slingerland 1997). The challenge in the current context is to use the geomorphic process model to map out (a) areas of net erosion (which would be unlikely to contain cultural material), (b) areas of net deposition, and (c) the age-versus-depth relationships associated with depositional features. The model will be tested and calibrated using data on late Quaternary sediment accumulation rates within selected drainage basins on Fort Riley, collected by William Johnson (see Chapter 3 below).

Our expectation is that the modeling effort, in addition to its contribution to the immediate problem at hand, will also contribute new insights into the ways in which the archaeological record is typically modified by post-depositional processes. Such information would be of great use to the cultural resources community at large. Further, an important potential spin-off application that we intend to explore is the application of the CHILD model for predicting erosional hazards as a result of contemporary landscape disturbance (e.g., due to training exercises).

One of the fundamental challenges to cultural resource managers lies in estimating the

likely distribution of buried archaeological sites. Often, estimates of where buried remains are most likely to occur must be made, at best, on the basis of only fragmentary field survey data. In the Fort Riley case discussed in the previous chapter, for example, the only data available were limited surface finds. In designing new surveys, cultural resource managers are typically constrained by serious time and budget constraints. In these respects, cultural resource managers face many of the same challenges as those who deal with other subsurface resources, such as hydrocarbons, mineral deposits, and ground water. In each case, the resource in question lies below ground with an unknown distribution. The manager's task is to make the best possible estimate of resource distribution given fragmentary information and a limited budget.

With prehistoric cultural resources, just as with geological resources, the distribution of material in the subsurface is closely related to the geologic setting and history. The spatial distribution of buried prehistoric sites depends in part on patterns of erosion and sedimentation since the cultural material was deposited. The close connection between landform position, surficial geology and archaeological potential is well illustrated by an example from Fort Riley, Kansas. Figure 2.1 shows a schematic cross section from the Forsyth Creek watershed, mapped by W.C. Johnson (see Chapter 3 herein). The cross-section is taken from two stream terraces. The alluvial fill within both terraces reveals a series of paleosols (ancient soils, now buried), which have been radiocarbon dated by Johnson (1998; see also Chapter 3 herein). The lower terrace contains alluvial sediment ranging from 6700 BP at depth to less than 1900 BP near the surface. The higher terrace contains older material, including deep alluvial fill dating back to the earliest well-documented occupation of north America at around 10,500 BP. A prehistoric site from this period was found at approximately four meters below the surface. This site, and others like it, would have been missed by traditional surface and shallow subsurface testing methods. In other landscape positions, however, archaeologically relevant deposits are considerably shallower and do not require deep testing.

The example in Figure 2.1 provides a useful illustration of how the potential depth of site burial, and the age of deposits and any associated cultural materials, vary systematically across a landscape. Because the variations are systematic and connected to geomorphic processes, information about the geomorphic context can be of tremendous value in estimating cultural resource potential and designing field surveys. Despite its importance, however, the geologic context is rarely taken into account in archaeological survey design or excavation.

This chapter describes the development of a prototype simulation system that addresses the need for geomorphic information in cultural resource management. We present a series of example simulations based on data from Wildcat Creek, Fort Riley, Kansas. These simulations provide a proof-of-concept illustration of the potential for using landform simulation modeling as a tool for developing more accurate and cost-effective cultural resource management solutions. We also discuss further steps that would be required to bring this effort beyond the proof-of-concept stage.

Approach

The distribution of archaeological resources at depth depends to a great extent on the 3D spatial distribution and depositional ages of geologic materials that were deposited during the time period of human habitation (e.g., during the latest Quaternary to Holocene in North America). It is virtually impossible to collect sufficient data to provide a complete, three-dimensional picture of the subsurface in any given location larger than a few square meters in extent. With the simulation technology developed in this project, however, it is now becoming possible to simulate the geologic processes that have been responsible for shaping the deposits typical of fluvial environments like the stream valleys of Fort Riley. By simulating the genesis of surficial deposits and their associated archaeological contents, it becomes possible to:

1. improve our ability to exploit geomorphic data by developing a deeper understanding of how erosion and sedimentation can influence 3D archaeological site distribution as a function of landform position, environment, and recent geologic history;
2. develop a "virtual archaeology" simulation system that can be used to test alternative survey and sampling methods in a low-cost, non-destructive fashion.

The approach is diagrammed in Figure 2.2. Note that simulation modeling can not, by itself, provide a means of precisely reconstructing the nature and extent of any given soil horizon in the field. Due to the stochastic nature of the processes involved, such reconstruction is never possible without prohibitively expensive and exhaustive field excavations. What process-based simulation does provide is a "virtual archaeological laboratory" that can act as a non-destructive test-bed for designing robust and economical resource management strategies, and can provide "training data sets" for conditioning and refining statistical models such as geostatistics and predictive modeling (see Chapter 1 herein).

The CHILD Model

The simulation model is an extension of the CHILD landscape evolution model (Figure 2.3). CHILD can simulate erosion and sedimentation in a river basin, over periods ranging from centuries to millennia or longer. The landscape is represented by a triangulated mesh of points, or nodes. A sequence of randomly-generated storm events create runoff that cascades downslope across this surface, in the process driving erosion and/or sedimentation at different points in the landscape. Beneath each point lies a sequence of layers of deposited material. When sediment is deposited at a given point, the sediment is added at the top of the sequence of layered strata and its depositional age is recorded. The CHILD model is discussed in detail by Tucker et al. (1999, 2000, and in review) and by Tucker and Bras (2000). Here, we focus on the rule set used in the geoarchaeological simulations.

In this initial phase of work, we have focussed on alluvial settings because of their high potential for buried archaeological sites and their general importance in prehistoric archaeology. Thus, the sub-set of process equations developed for this work, as well as the boundary conditions used, are tailored to the case of a typical meandering stream and its associated floodplains. However, the simulation framework is quite general and can in principle be extended to treat other types of processes and environments (e.g., aeolian dunes). The model capabilities and process equations relevant to this study are detailed below. The processes and boundary conditions are diagrammed in Figure 2.4.

Spatial Framework: Adaptive Mesh

In order to avoid the limitations associated with grid-based models, the terrain surface may be discretized as a set of points (nodes) in any arbitrary configuration. These nodes are connected to form a triangulated irregular mesh (Braun and Sambridge 1997; Tucker et al. 2000). The mesh is constructed using the Delaunay triangulation, which is the (generally) unique set of triangles having the property that a circle passing through the three nodes of any triangle will contain no other nodes (e.g., Du 1996). The use of an irregular spatial framework offers several important advantages: (1) the model resolution can vary in space in order to represent certain landscape features, such as floodplains or regions of complex terrain, at a locally high level of detail (e.g., Figure 2.5); (2) adaptive remeshing can be used to adjust spatial resolution dynamically in response to changes in the nature or rates of processes occurring at a particular location (e.g., Braun and Sambridge 1997; Tucker et al. in press; and examples below); (3) nodes can be moved horizontally as well as vertically, making it possible to simulate lateral and surface-normal, as opposed to purely vertical, erosion (as, for example, in the cases of meandering channels and cliff retreat); (4) nodes can be added to simulate lateral accretion of, for example, point bars in meandering streams or accretionary wedges at active margins; and (5) the terrain can be coupled with 3D kinematic or dynamic models of tectonic deformation in order to simulate interactions between crustal deformation (e.g., shortening, fold growth) and topographic change. The data structures used to implement the triangular mesh are described by Tucker et al. (in press). In the context of geoarchaeological simulation, the irregular mesh allows for dynamic movement of a laterally migrating main stream channel.

Temporal Framework: Storms and Floods

One of the challenges in modeling terrain evolution lies in addressing the great disparity between the time scales of topographic change (e.g., years to geologic epochs) and the time scales of storms and floods (e.g., minutes to days). Most previous models of drainage basin evolution have dealt with this disparity by simply assuming a constant average climatic input (e.g., a steady rainfall rate or a "geomorphically effective" runoff coefficient). This approach, while computationally attractive, has three drawbacks: (1) it ignores the influence of intrinsic climate variability on rates of erosion and sedimentation (e.g., Tucker and Bras 2000); (2) it fails to account for the stochastic dynamics that arise when a spectrum of events of varying magnitude and frequency acts in the presence of geomorphic or hydrologic thresholds; and (3) the approach typically relies on a poorly calibrated "climate coefficient" that cannot be directly related to measured climate data.

In order to surmount these limitations, and to address the role of event magnitude and frequency in drainage basin evolution, CHILD uses a stochastic method to represent rainfall variability. The method is described in detail by Tucker and Bras (2000), and is only briefly outlined here. In solving the continuity equation, the model iterates through a series of alternating storms and interstorm periods (Figure 2.4-C). Following the Poisson rainfall model developed by Eagleson (1978), each storm event is associated with a constant rainfall intensity, P, a duration, T_r, and an inter-arrival "waiting time", T_b. For each storm, these three attributes are chosen at random from exponential probability distributions, the parameters for which can be

readily derived from rainfall data (e.g., Hawk 1992; Boardman and Favis-Mortlock 1999). Storms are approximated as having constant intensity throughout their duration, and the same assumption is also applied to the resulting hydrographs. Runoff-driven transport and erosion processes are computed only during storm events. Other processes, including diffusive creep transport and tectonic deformation, are assumed to occur continuously, and are updated at the end of each interstorm period.

Note that the model imposes no special restrictions on time scale (aside from the fact that it is designed for periods longer than the duration of a single storm). For simulations involving terrain evolution over thousands to millions of years (e.g., Tucker and Slingerland 1997), however, it becomes computationally intractable to simulate individual storms. For many applications this problem can be overcome by simply amplifying the storm and interstorm durations. As long as the ratio T_r/T_b remains the same, the underlying frequency distributions are preserved. Long-term variations in rainfall frequency or magnitude (such as those related to late Quaternary climate fluctuations) can also be simulated by allowing the three rainfall parameters to vary in time.

Lateral Stream Channel Migration (Meandering)

Owing to the large difference in scale between individual stream channels and their drainage basins, channels are generally treated as one-dimensional entities in landscape evolution theory. For many applications, this choice is entirely appropriate; for others, however, it is problematic because it neglects the role of floodplains as sediment buffers (e.g., Trimble 1999) and as host deposits for archaeological resources. This limitation is particularly severe in analyses of watershed responses to perturbations (e.g., Tucker and Slingerland 1997). At the same time, the morphologic and stratigraphic development of floodplains are important problems both in their own right (e.g., Mackey and Bridge 1995; Moody et al. 1999) and for geoarchaeological applications. These issues have motivated the development of a simple "rules based" model of channel meandering, based on the principle of topographic steering, which is capable of modeling channel planform evolution on time scales relevant to valley, floodplain, and stream terrace development (Lancaster 1998; Lancaster and Bras in review).

Lateral channel migration is implemented in CHILD by first identifying main channel (meandering) nodes on the basis of a drainage area threshold. Lateral migration of these nodes occurs perpendicular to the downstream direction, and the rate is proportional to the bank shear stress:

$$\vec{\zeta} = E_{eff}\tau_w\hat{n} \tag{1}$$

where τ_w is the bank shear stress determined by the meandering model of Lancaster and Bras (2000, in review; see also Lancaster 1998); n is the unit vector perpendicular to the downstream direction; and E_{eff} is the effective bank erodibility. We use the meandering model of Lancaster (1998) to find τ_w in (1) as a function of channel curvature upstream. Movement of a channel node

indicates that the channel centerline has moved, i.e., that one bank has been eroded while deposition has occurred at the other. As the channel migrates, existing nodes are deleted from the moving channel's path, and new nodes are added in the moving channel's wake. Node movement and addition require re-determination of node stratigraphy.

Example

An example simulation incorporating the stream meander model is shown in Figure 2.6. Here the model is configured to represent an idealized segment of floodplain, with a large stream (point source of discharge) entering at the top of the mesh and exiting at the bottom. The hydrology and initial topography are patterned after Wildcat Creek on Fort Riley, as discussed below. In this example, the mainstream elevation is forced with a series of cut-fill cycles (representing millennial-scale climate impacts), while the stream planform is free to migrate laterally. Each point along the main channel is moveable. Dynamic remeshing is used to ensure that the mainstream is adequately resolved. Whenever a moving channel point comes very close to a fixed "bank" point, the latter is removed from the mesh. To ensure an adequate level of spatial resolution within the floodplain, a new point is added in the "wake" of a moving channel point whenever the moving point has migrated a given distance away from a previously stored earlier location (which is then updated). The net result is that the floodplain is modeled at a locally high resolution relative to the surrounding uplands (Figure 2.6).

Floodplains: Overbank Sedimentation

Valley-fill sediments often contain an important record of paleoclimate, paleo-geomorphology, and prehistory (e.g., Johnson and Logan 1990). In the central Great Plains environment discussed in Chapters 1 and 3 of this report, fine overbank sediments appear to constitute the bulk of the alluvial fill. Most studies of the formation and dynamics of river basins have treated streams as essentially one-dimensional conduits of mass and energy. Yet valley-fill sediments are inherently three-dimensional features, and to model their stratigraphy properly requires an alternative approach. The one-dimensional approach cannot, for example, resolve important aspects of alluvial stratigraphy such as the distribution of channel and overbank deposits (e.g., Mackey and Bridge 1995). Motivated by this limitation, CHILD includes the capability to model overbank sedimentation using a modified form of Howard's (1992) floodplain diffusion model. Under this approach, the rate of overbank sedimentation during a flood varies as a function of distance from a primary channel and local floodplain topography (Figure 2.4-E). Average rates of floodplain sedimentation are known to decay with distance from the source channel due to diffusion of turbulent energy. The local rate of sedimentation is also presumed to depend on the height of the floodplain relative to water surface height. During a given storm event, the rate of overbank sedimentation at a given point is

$$D_{OB} = (\zeta - z)\mu \exp(-d/\lambda) \tag{2}$$

where D_{OB} is the vertical deposition rate (dimensions of L/T), z is local elevation, d is the distance between the point in question and the nearest point on the main channel, ζ is the water

surface height at the nearest point on the main channel, μ is a deposition rate constant (T^{-1}), and λ is a distance-decay constant. "Main channel" is defined on the basis of a drainage area threshold; typically, the model would be configured with a large channel fed in as a boundary condition for this type of application, so that there would be no ambiguity about what constitutes a primary channel (e.g., Figure 2.4). Water surface height is computed as the sum of bed elevation, z, and water depth, H, using a simple empirical hydraulic geometry approach for H:

$$H_b = k_h Q_b^{m_{hb}}, \qquad H = H_b (Q/Q_b)^{m_{hs}} \tag{3}$$

where H_b is bankfull channel depth, Q_b is a characteristic discharge (such as bankfull or mean annual), k_h is bankfull depth per unit scaled discharge, and m_{hb} and m_{hs} are the downstream and at-a-station scaling exponents, respectively (Leopold et al. 1964). Equation (2) is only applied for events in which $H > H_b$.

Stratigraphy

Each node in the model is underlain by a column of material divided into a series of layers of variable thickness and properties (Figure 2.7). Physical attributes associated with each layer include the relative sand and gravel fractions (if applicable), the median grain size of each sediment fraction, and the material detachability coefficient, k_b. These properties are assumed to be homogeneous within a given layer.The time of most recent deposition is also stored for each layer, so that chronostratigraphy can be simulated. Finally, each layer also records the amount of time it has spent exposed at the surface, a quantity here referred to as the exposure age. Exposure age is a key archaeological attribute: all else being equal, the probable artifact content is expected to be higher in sites that have a long surface-exposure history, as compared with those subject to either rapid erosion (in which case artifacts are lost) or rapid deposition (in which case a given deposit thickness will represent only a short time interval and be relatively artifact-poor).

The active layer depth is fixed in time and space. When material is eroded from the surface, the active layer is replenished with material from the layer below. The active layer texture and time of surface exposure are then updated as a weighted averaged between the current properties of the active layer and those of the layer below. During deposition, material from the active layer is moved into the layer below before material is deposited into the active layer, so that the active layer depth remains constant. The layers below the active layer have a maximum depth; when this depth will be exceeded due to deposition, a new layer is created.

Simulation and Results

Model Setup and Inputs

For purposes of this initial-phase study, the model was configured with initial and boundary conditions based on lower Wildcat Creek. Wildcat Creek is the largest of the Fort Riley

watersheds, and is characterized by a wide valley floor that contains late Quaternary and Holocene terraces in addition to the modern floodplain, as mapped by Johnson (1998; see Chapters 1 and 3 herein). The potential for both near-surface and buried sites is quite high, as discussed elsewhere in this report.

The model was configured to represent an idealized segment of the Wildcat Creek valley and its adjoining uplands. The model domain consists of a 1 km by 1 km region inset (initially) by a 200-m wide valley. Uplands-to-valley relief of 50 m is based on topographic maps of Wildcat Creek. A discharge point source at the upper end of the mesh is used to represent the inflowing creek, with a drainage area of 192 km^2 (equal to the size of the Wildcat catchment at the town of Manhattan). Rainfall parameters derived by Hawk (1992) from data at the Norfolk, NB weather station were used (this was the closest of the stations analyzed by Hawk [1992]). Bankfull discharge was estimated from USGS gaging station data at Manhattan, KS. Hydraulic channel geometry (width and depth) parameters were estimated from empirical regressions published by Leopold and Maddock (1953). The channel elevation is forced to follow the same floodplain elevation history as that of the Pomme de Terre River in southern Missouri, estimated from radiocarbon terrace dates by Brakenridge (1980) (see Figure 2.8). The outlet point follows Brakenridge's curve, and the elevation of all points upstream is calculated assuming a constant channel slope.

Qualitative Comparison of Morphology of Wildcat Creek and Model Results

Planar Views

Johnson (1998) mapped two terrace groups, along with the active floodplain, on the lower Wildcat Creek (Figure 2.9). Terrace 2, the older terrace, is much more expansive than Terrace 1, the younger terrace. The numerically simulated terraces of Wildcat Creek are illustrated in Figure 2.10, which is a shaded elevation map of the meander-belt only. The most notable terrace is shaded in red and is at an elevation of about nine meters. Figure 2.11 illustrates the evolution of the meander-belt over time. The figure shows surface material color-coded by the time of deposition. The last panel (2.11-E) represents the present. The areas colored in the two shades of purple on Figure 2.11-E are the same as the red-shaded areas of the elevation map in Figure 2.10. The age of this material corresponds to the channel rising period from 7,750 years BP to 5,000 years BP and the channel falling period from 5,000 BP to 4,750 BP (see Figure 2.8). Of course a complete map of surface ages would not be available from a field survey; however, from our simulated terrain, we can identify this terrace both by age and elevation. This terrace might be comparable to Terrace 2 from Johnson's Wildcat Creek map (Figure 2.9).

The elevation map in Figure 2.10 also clearly indicates the active floodplain, shaded in aqua blue. The active floodplain is currently at an elevation of four to five meters, as indicated from the elevation map and also Figure 2.8.

From the simulated terrain, it is difficult to discern what else would be labeled as distinct

terraces. There are areas with elevations in between the oldest terrace and the active floodplain, most notably the area shaded orange, yellow and green in the middle of Figure 2.10, with elevations ranging from eight to six meters. From the surface age map (Figure 2.11) we see that the material at an elevation of about eight meters was laid down by a different, earlier episode than that which produced the material at an elevation of about six meters. Given only the simulated elevation map, most likely two distinct terrace groups would be identified. First, the older terrace would be the one at about nine meters (shaded in red on Figure 2.10), which was already discussed. The small fragments of topography which are still left at eight meters (orange-colored on Figure 2.10) would probably be grouped with this older terrace. Second, a younger terrace at six meters (green-colored on Figure 2.10) could also be identified. Two other small fragments of this terrace also remain along the left bank of the meander belt. Nevertheless, with the additional knowledge of the surface ages available, one recognizes that the material at eight meters (orange on Figure 2.10) is a separate terrace. This is only possible with the model.

Cross-Sections

The stratigraphic component of CHILD allows for identification of the age of not only surface alluvium but of the entire stratigraphy. Figure 2.12 shows a planar view of the meander-belt indicating the location of three cross-sections. The vertical structure of the time of deposition of alluvium at these cross-sections is shown in Figure 2.13. The darkest blue material in this figure represents the initial material from the start of the numerical simulation, hence the "basement" material is all dark blue. Some numerical errors are apparent from the blue stripes of ancient material in the cross-sections, but the overall patterns in the ages of alluvium are correct.

The numerically-simulated cross-sections can be compared with the mapped cross-sections from Forsyth Creek (Figure 2.1). As was discussed earlier, Figure 2.1 clearly illustrates that the age of deposits at a given absolute elevation can vary systematically across the landscape. The same phenomenon occurs in the simulated data. For example, in cross-section A, moving across the section at an elevation of about six meters, you find material deposited very early on in the simulation, colored as dark blue, younger material which is shaded in yellow, and even younger material which is shaded in orange. The same phenomenon is observed in the two other cross-sections.

The cross-sections also illustrate other interesting points about the geomorphic history. For example, a historical channel cut-off can be identified in cross-section A. The green/blue-aged material (surface of terrace labeled A1) and yellow-aged material (surface of terrace labeled A3) were deposited before the orange-aged material which makes up terrace A2 in Figure 2.13. This implies that at one time the channel was running between terrace A1 and A3. Because terrace A3 is older than terrace A2 and terrace A3 is also between terrace A2 and the current channel position (V-shaped notch in the red-aged material), the channel could not have swept across the meander belt directly from where it was at the orange time to its current position, but instead a cut-off must have occurred upstream. Furthermore, in cross-section B, a deposit of younger yellow-aged material (terrace B2) is abutting much older dark blue deposit (terrace B1). The channel must have meandered away from the older blue-aged deposit and then traveled across the meander belt again, cutting into the blue-aged deposit and leaving discontinuity in ages of the two adjacent deposits.

Archaeological Application

Value of Three-Dimensional vs. Two-Dimensional Modeling

A typical two-dimensional archeological survey would sample surface material to gain better insight as to where to dig for prehistoric artifacts. As illustrated from the trench data taken from Forsyth Creek, the material at the surface doesn't necessarily represent what may be found below the surface. This is also apparent from the simulated cross sections. The concept is well illustrated by Figure 2.14, which shows the age distribution of only surface deposits (top 10 cm) in comparison with the age distribution of all deposits. If one samples only the surface sediments, it is very likely that the survey would completely overlook any material older than 8,500 years BP corresponding to the Paleoindian culture. However, a relatively large percentage of the deposits date back before 8,500 years BP, these deposits just happen to be buried. Figure 2.14 also shows that more recently deposited material can be found at some depth below the surface, but not at the surface; for example, alluvium deposited between 3,000 and 4,000 years BP is only found below the surface. Presuming that the age of alluvium is a good indicator of the age of artifacts found within it, the above example illustrates why the distribution of surface ages is not a complete indicator of the richness of artifacts.

Simulation of Artifact Deposition

In order to illustrate the use of a geomorphic model in an archaeological problem, we simulate the deposition of artifacts. We assume that the age of any deposited artifacts at any location (in x, y, and z) would be the same age as that of the deposited alluvium. This implies that artifacts are only laid down on the surface and that when a deposit is eroded away, any artifacts are carried along with it. The simulation does not consider erosion, transport, and redeposition of artifacts. We also use the exposure age of material, introduced earlier in the stratigraphy section, as an indicator of the likelihood that a deposit will contain artifacts. The longer a deposit has remained at the surface, the higher chance it has of containing artifacts.

We assume that deposition of artifacts can be modeled as a Poisson arrival process. Consider a patch of ground of unit surface area. Following the standard derivations of the Poisson arrival process (e.g., Eagleson 1978), the probability of a single artifact (or "feature"; here we use the term artifact for simplicity) being deposited during a time interval Dt is P. The chance of more than one arrival in Dt is negligible. This leads to the binomial distribution for probability $P_q(v)$ of the number of new artifacts deposited, q taking a value v, during time interval $t=mDt$:

$$P_q(v) = \binom{m}{v} P^v (1-P)^{m-v}$$

As Dt approaches zero, this becomes the Poisson distribution,

$$P_{q|t}(v) = \frac{(\omega t)^{v} e^{\omega t}}{v!}$$

where ω is the arrival rate of artifacts.

Using this probability density function, we can run Monte-Carlo sampling trials on different sampling scenarios to discern how successful these different schemes would be. We perform our trials as follows. First we decide where to sample. In each of the different sampling scenarios we uncover the same volume of sediment. Once we decide where and how deep to investigate, we find the amount of time that the sediment in our "pit" was exposed at the surface, and therefore the amount of time it was accumulating artifacts. Given an arrival rate of artifacts, the Poisson distribution above allows us to simulate the number of artifacts found in our pit. We do this at every location in our sampling scenario to compute the total number of artifacts found in a single sampling campaign. For each digging scenario we run 41 different Monte-Carlo simulations to determine the average number of artifacts found using a particular sampling scheme.

Figure 2.15 illustrates the four different sampling schemes tested. The first scheme does not use any knowledge of the geomorphic history. Thirty-six pits, each 0.5 meters deep and 1.0 square meter in area, are sampled on a regular grid. Some points are moved slightly so that we do not sample in the current channel. Using an arrival rate of 1.0 artifact per year spent at the surface, this sampling scenario will uncover, on average, 3402 artifacts (see Table 2.1). The second scheme is a more educated sampling scenario. Here we only sample on the two oldest terraces, but we still investigate 36 pits, each 0.5 meters deep and 1.0 square meter in area. With scheme two, and an arrival rate of 1.0 artifact per year spent at the surface, the average number of artifacts recovered is 6,034, almost double that of the first scheme. In the third scheme, again we sample 36 pits of 0.5 meters depth and unit area, but this time on two terraces which are not as old as those sampled in scheme two. The average number of artifacts recovered (with ω = 1.0) is 3,055, even less than scheme one which disregards the geomorphology. In the fourth scheme, we only sample on the oldest terrace, but this time we investigate 18 pits of unit area which are 1.0 meter deep. This scheme recovers 4,522 artifacts, more than scheme one, but less than using the second scheme which investigates only shallower pits on the older terraces. Changing the arrival rate (ω) does change the total number of artifacts found, however it does not affect how

Table 2.1. Results (number of artifacts) from Monte Carlo sampling (41 realizations each) of different subsurface testing schemes with different arrival rates (*w*, preserved artifacts per year).

	***w* = 1.0**	***w* = 0.25**	***w* = 0.1**	***w* = 0.01**
Scheme 1				
maximum	3476	1431	572	73
mean	3402	1346	532	55
minimum	3308	1244	457	39
Scheme 2				
maximum	6142	3003	1233	130

mean	6034	2903	1159	113
minimum	5938	2515	1110	81
Scheme 3				
maximum	3162	1075	442	57
mean	3055	1016	414	41
minimum	2956	950	367	30
Scheme 4				
maximum	4640	2144	869	93
mean	4522	2039	809	80
minimum	4444	1933	763	59

well one scheme does relative to another, which is the important point of this example. A sampling scenario directed by knowledge of the geomorphic history is far more effective in uncovering archaeological artifacts.

In the above experiments, the material which is presently at the surface has been there far longer than any of the material buried below. This is illustrated in Figure 2.16, which shows the same cross sections as in Figure 2.13, but this time shaded by exposure age. Exposure age is shown using a log scale in order to highlight variations. The material colored in red on this figure spans about 4,000 years of exposure age. The material which has the longest exposure time is found at the surface in this particular experiment. Because the probability of finding an artifact increases with exposure time, deeper sampling doesn't greatly increase the number of artifacts found. Nevertheless, one does need to sample deeper deposits to find the oldest material, which will probably contain important older artifacts (see Figure 2.13).

Conclusions

This chapter shows the potential of computer simulations in the characterization of military training sites from a geoarchaeological perspective. It should be clear that from data and model results the geomorphic and stratigraphic history of a site controls the occurence of archaeological sites. A planar, surficial sampling can be misleading in terms of the archaeological value of the site. The chapter illustrates how the surface can contain sediments of different ages side by side. It also shows that depth from the surface alone is not a good indicator of deposition age. The chapter illustrates how the length of time a particular deposit spends at the surface influences the number of artifacts found in the strata. More importantly the chapter shows that the "rich" strata may be buried under less or more productive deposits. The chapter also illustrates how surface characterizations may misclassify terraces and other geologic expressions of interest. It should also be clear that erosion processes may eliminate traces of habitation. The "intensity" of the geological fluvial processes will control the level of "disturbance" of the sites.

The main message is that three dimensional characterization of geologic history, the definition of stratigraphy, adds significant value to the archaeological knowledge of sites. The three dimensional simulations help in gaining that three dimensional knowledge of sites. The numerical models can:

- Be a platform to test hypotheses of stratigraphic evolution;
- Help us understand field data;
- Serve as virtual realities where sampling strategies or training can occur;
- Ultimately the models could assimilate observations in the field to produce conditional simulations or possible "scenarios" for the sites being investigated;
- Serve as a land management tool to control the use of valuable sites. This could mean prediction of erosion given a particular pattern of use or the evaluation of remediation strategies.

The potential of the models is large and a lot remains to be done to exploit that potential.

CHAPTER 3
Late-Pleistocene and Holocene Landscape Reconstruction and Model Validation through Geoarchaeological Investigations

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Introduction

Many years ago, archaeologists recognized that the preserved record of past cultural activities is evidence of, with varying degrees of accuracy, both (1) the articulation of human groups and their environment and (2) the effects of post-occupational processes on the material remains of those activities (e.g., Schiffer 1976; Binford 1981; Wood and Johnson 1978; Gladfelter 1985; Johnson and Logan 1990; Waters 1992). As a result, we have come to realize that by far, most preserved cultural remains (1) are situated in valleys because of the rich resource base locally available and (2) are buried, often deeply, by the accumulation of overbank stream deposits and accretion of alluvial fans.

Sampling methods for regional and local archaeological surveys have been articulated by many researchers (e.g., Warren and O'Brien 1981). Because these traditional approaches consider only the surface and upper few centimeters, studies have typically failed to address the pervasive problem of erosion (removal/destruction) and deposition (burial), and how they may skew the archaeological record. In recent years, archaeologists and earth scientists have routinely joined ranks to address the issue of geomorphic factors that affect site distributions at all scales.

Fort Riley

Geoarchaeological research on Fort Riley represents a high-resolution examination of the alluvial record, with the goal of identifying and mapping the remnants of the sedimentary record that contain the potential for cultural remains. Through extensive field investigations and the application of radiocarbon dating and other procedures, alluvial surfaces and fills have been mapped and dated.

Human populations rose to levels sufficient to leave a widely detectable record in the central Great Plains approximately 11,500 years ago, i.e., the Paleoindian cultures (Holliday 1997; Hofman and Graham 1998; Holliday 2000). This cultural period coincides with major landscape adjustment to climate change associated with the end of the Last Ice Age: changes in temperature and precipitation patterns and vegetation communities altered the surface hydrology and associated erosion and deposition. Stream valleys entrenched to remove most of the late-Pleistocene fill; the exceptions were large alluvial fans, many of which completely or partially

survived the entrenchment. Consequently, the oldest of valley-fill deposits generally date from about the time that human occupancy was expanding.

Developing a representation of valley-fill deposits, associated stratigraphic histories, and ages of sufficient detail is an extremely time-consuming task. Because of the time involved in developing a detailed depiction of the valley fills, or "sediment packages" found within valleys, two stream systems were selected for detailed investigation: Forsyth Creek, a medium-sized tributary in the south-central part of the installation, and Wildcat Creek, the largest of the involved stream systems and located on the northeast side of the installation (Figure 3.1). Topography of the basins can be appreciated in both topographic map and 3-D block diagram renderings (Figures 3.2, 3.3, 3.4). Data derived from the Wildcat Creek system were applied to the CHILD Model, while those from the Forsyth Creek system were used in a comparative context to examine the inter- as well as intra-basinal relationships.

Alluvial Landscape Mapping

Two basic stages were involved in the reconstruction of the alluvial landscape within the Fort Riley military reservation. First, reconnaissance mapping of alluvial landforms was accomplished using stereoscopic coverage of black and white aerial photography. At this stage, the flood plain, terraces, and alluvial fans were delineated. The second and most costly (and time-consuming) stage of the reconstruction consisted of (1) documenting the stratigraphy and age of various terrace and alluvial fan fills, and subsequently (2) correlating various fills with the alluvial surfaces, i.e., definition of the *morphostratigraphy* (nature of the surface identifies or implies the underlying fill stratigraphy).

The second stage involved (1) foot survey of each valley from the channel bed or water's side to correlate fills exposed in channel banks with their overlying surfaces, and to search for exposed sections worthy of documentation; and (2) exploration of the unexposed valley fills using (a) motorized, trailer-mounted coring machines, (b) hand augering and coring devices, and (c) backhoe trenching. Exposures (natural and backhoe trench) and cores were fully described and documented, and sampled where appropriate for laboratory analyses. Although all subsurface investigations were done at relatively high spatial resolution, selected valley reaches were cored at a particularly high-resolution (five-meter grid). All tolled, forty backhoe trenches were excavated in the two basins, and each of these requires a half day to excavate, describe, sample and backfill, i.e., two trenches per day was typical. Nearly one hundred bank exposures were mapped, documented, and selectively samples. Machine and hand-extracted cores numbered in the hundreds due to the intensity of the subsurface exploration. Machine coring was done to extract deep (long) cores (up to 20m), and shallow (up to 3m) hand coring was done between the deeper cores. Coring and backhoe trenching were done along transects established in each basin (Figures 3.5, 3.6), and in intervening reaches as needed to completely characterize and differentiate fills, and to document the morphostratigraphic relationships.

All surface and subsurface information was entered into geographic information system (GIS) software to create an integrated database. These field- and aerial photograph-derived data were electronically overlain on other data layers, including geology, road systems,

orthophotography, soils, hydrography, road system, and GPS coordinates of all cores and exposures.

Analytical Methods: Rationale, Procedures, and Results

Rationale

In order to temporally correlate the various alluvial fills within the basins, several stratigraphic approaches were taken. The various signals produced by the stratigraphic parameters were instrumental in dating and correlating the fills. In addition, some of the parameters provided valuable information about the prehistoric environments in the Fort Riley area. The various stratigraphic approaches included:

(1) *Lithostratigraphy* (sedimentology of the fills): Each exposure and core was described in detail in order to characterize the associated fills with regard to sediment size and variation.

(2) *Pedostratigraphy* (buried soils within the fills): Most stratigraphic sequences examined contained buried soils, often referred to as *paleosols*. The relative sequence of buried soils and their associated degree of develop was used for correlation among fills. The buried soils represent former times of flood-plain stability and, consequently, are associated with the highest concentrations of archaeological materials.

(3) *Biostratigraphy* (biological remains and signals within the fills): All fills contain two important types of biological information that may be used in correlating the various fills: stable carbon isotope ratios ($\delta^{13}C$) and biogenic opal. The former represents an isotopic imprint induced by the vegetation, and the latter microscopic silica bodies diagnostic of the plants within which they were produced. Both of these signals reflect the prevailing climate because they record the associated vegetation. The resulting time series for these parameters derived from a stratigraphic sequence was used to correlate among fills.

(4) *Magnetostratigraphy* (nature of the magnetic minerals in the fills): The rock magnetic signature of a given fill is indicative of the type and concentration of magnetic minerals and yields two types of primary information: the degree of weathering that the sediments have experienced and the nature of the source(s) of the sediments. Two parameters were used: susceptibility (concentration-dependent parameter) and frequency dependence of susceptibility (size- and source-dependent parameter). As with the previous approaches, the resulting time series within a stratigraphic sequence was used to correlate among fills.

Procedures

Radiocarbon dating.

Radiocarbon dating has been a valuable tool in late-Quaternary studies for more than 40 years. The numerical age control on stratigraphy provided by radiocarbon dating permits determination of the timing of various erosional and depositional events and affords the opportunity to calculate the rate and magnitude of environmental and geomorphic change. In particular, radiocarbon dating has, in recent years, become critical to geoarchaeological research. Materials for radiocarbon dating are, however, limited in late-Quaternary deposits of the central Great Plains. Late-Pleistocene (Last Ice Age) vegetative cover of the region has produced only

scattered wood and charcoal in loess and alluvium, and grass cover of the Holocene (Postglacial Period) resulted in even fewer datable macrofossils. Earth scientists and archaeologists frequently use organic carbon preserved in buried soils and sediments for radiocarbon age control. There is, however, considerable debate about the accuracy of ages determined from buried soils and sediments, despite general acceptance of radiocarbon dating. Some argue that resulting age determinations are fraught with problems (e.g., Polach and Costin 1971; Gilet-Blein et al. 1980; Geyh et al. 1983; Forman and Miller 1989; Hammond et al. 1991), while others maintain that ages provide relatively reliable age control (e.g., Matthews and Dresser 1983; Haas et al. 1986, Martin and Johnson 1995). Radiocarbon dating of organic carbon in soils and sediments has become routine in recent years and is producing results comparable to charcoal and wood. Dating such materials does, however, require greater care in collection, preparation, and interpretation.

Various factors affect the quality, or accuracy of radiocarbon ages obtained from soils or sediment. The first area of potential problems relates to sample collection. Where the sample is collected in the stratigraphic sequence determines what event it represents temporally; this is especially true for buried soils. One may collect samples from the top, bottom, and middle parts of a soil, or draw a composite sample integrating the entire sampled horizon. The latter is the least desirable from most perspectives. W.C. Johnson and his students typically collect from 2 to 5 cm-thick layers in the bottom and top of the buried A horizon, with the intent of estimating the onset and termination, respectively, of pedogenesis. In buried alluvial soils, the difference between the top and bottom of the A horizon can range up to 1000 years (Johnson and Martin 1987; Johnson and Logan 1990). The quantity of sample collected also relates to the accuracy of the age. In order to have a sufficient sample size for conventional radiocarbon analysis, approximately 8 kg (4 one-gallon *Ziploc* heavy duty freezer bags) are collected. Less is required if the sample is collected from a buried soil with a relatively high organic matter content, and perhaps more if from sediments expressing minimal or no pedogenesis. If an insufficient amount of ^{14}C-containing gas is produced, the standard deviation associated with the age will increase.

Two adjustments, correction and calibration, can be made in radiocarbon ages to improve the quality and interpretability of the ages. Because the carbon pathway differs among plants, ratios among the isotopes of carbon in plant tissue vary, which in turn results in ^{14}C determinations which may not represent the true radiocarbon age. This process, isotopic fractionation, may produce anomalously young ages (Taylor 1987), particularly in the central Great Plains, where many of the grass species tend to over-represent the ^{14}C actually in the atmosphere. A procedure based on a standardized ^{13}C concentration corrects radiocarbon ages for the effects of isotopic fractionation. If an age determination is not corrected, it may be inaccurate by hundreds to thousands of radiocarbon years, resulting in potential interpretation problems. Another adjustment involves changes in the concentration of radiocarbon in the atmosphere through time; this change has resulted in a disparity between radiocarbon and calendar years. As a consequence, radiocarbon ages younger than about 18,400 yr BP can be calibrated to calendar ages using a relationship established with tree rings and corals. Calibrated ages are easily derived using software (CALIB ver. 4.2) developed by Stuiver and Reimer (1993).

The bulk samples were prepared using the following procedure (Johnson and Valastro 1994):

1) disaggregating the sample

(a) placing each bag (e.g., one-gallon *Ziploc*) of the sample into a 20-quart stainless steel or aluminum pot; filling the pot with distilled water; disaggregating with a large perforated stainless steel spoon or specially modified electric mixer; covering and allowing the sample to stand overnight or longer for complete disaggregation (some samples required repeated stirring);

2) sieving to remove floating debris and sand-size particles:

(a) stirring and skimming off floating debris with 60-mesh sieve until clear;

(b) passing the sample through a 230-mesh sieve over the sink and discarding the water and sediment (sand and larger);

3) transferring the sample to beakers:

(a) siphoning the pots and flushing the sediment into the 4-liter beakers using a distilled water jet; filling the beakers to within 2 inches of the top;

4) oven drying:

(a) siphoning the supernatant from the beakers.

(b) covering the beakers with aluminum foil and placing the beakers in the oven at 100° C until the sediment has dried completely, forming a cake;

5) pulverizing:

(a) removing the dry cake from the beakers and pulverizing.

After preparation at the University of Kansas, samples were submitted to the Radiocarbon Laboratory at the Illinois State Geological Survey for conventional radiocarbon dating. There, prior to burning for gas production, the samples are treated by boiling in 2N HCl for one hour in order to remove $CaCO_3$ and any dolomite that might be present.

Rock magnetic analyses.

The primary carriers of magnetism (iron oxides, iron sulfides and manganese oxides) usually comprise less than 5% of the sediment mass. These magnetic minerals are, however, common in terrestrial materials and extremely sensitive to environmental conditions. Since it is difficult to separate out these minute magnetic minerals in order to study them, the magnetic characteristics of the sediments are usually characterized by one of the bulk properties, magnetic susceptibility, which is measured using a non-destructive technique. Magnetic susceptibility is a measure of the extent to which a sample becomes more strongly magnetized when a small alternating magnetic field is applied, or simply the ratio of the induced magnetism to the strength of the applied field.

Whereas susceptibility provides information on magnetic concentration, a related parameter, frequency dependence of magnetic susceptibility (FD), provides information on the magnetic grain size. FD is the percent difference between susceptibility measured at a low-frequency applied field compared to its measurement at an applied field with a higher frequency. Unfortunately, FD measured using only fixed low and high frequencies, as is the case with existing instrumentation, will discriminate only a portion of the total superparamagnetic (very small magnetic material) population. With the instrumentation currently being used, only the presence of grains between approximately 18 and 20 nm in diameter (very fine clay size) can be

detected. Even so, FD values are typically much higher in soils than in intervening sediment, reflecting abundant pedogenic material.

Although susceptibility is largely a product of magnetic mineralogy and concentration, other factors come into play. Some of these factors include size and shape of the magnetic grains, frequency of the applied field, and sample size and shape. By controlling for the latter variables, controls on susceptibility reduce to magnetic grain size and shape, in addition to magnetic mineralogy. Magnetic grains fall largely into three groups, but not exclusively on the basis of size: multidomain, single domain, and superparamagnetic (largest to smallest). Since grain shape has so little influence on the susceptibility, variations in shape are easily accommodated in the algorithms employed. Magnetic susceptibility is controlled mainly by the volume of ferrimagnetic minerals in the sediments being analyzed. Magnetite is almost always the most important of the magnetic minerals.

Weathering and pedogenesis bring about dramatic changes in the magnetic character of sediments, the processes that make application to this study possible. Chemical and biochemical changes in unconsolidated sediments affect magnetic properties through the release, via weathering, of magnetic grains from previously existing sediments, the release of iron in ionic form from iron-bearing minerals, modification of the amount of diluting substances such as calcium carbonate and some clays, and formation of magnetic through the activities of bacteria and algae, especially magnetotactic bacteria. Further, physical weathering through its mechanical change in size, shape, and associated sorting of magnetic grains may affect bulk magnetic characteristic under certain circumstances. Fire has an appreciable effect on the magnetic susceptibility in that hematite is variably altered to magnetite and maghemite during combustion; buried burned surfaces, for example, show up dramatically in the susceptibility measurements, as does the related phenomenon, lightening strikes, albeit rarely. Pedogenesis, which involves chemical and physical weathering, has a major impact on the susceptibility and FD. All well-drained soils tend to exhibit a high susceptibility signal, whereas poorly drained/gleyed soils usually have low susceptibility values due to dissolution of the ferrimagnetic minerals under the reducing conditions. The array of susceptibility and FD patterns in soils is varied, e.g., some exhibit a general bulge in susceptibility over the entire soil and a high in FD within the B horizon where the fine secondary clay minerals are concentrated.

Of primary importance to the research at Fort Riley is the application to detecting weathering zones and pedogenesis, i.e., buried weathering zones and soils within the alluvial record. Through the use of susceptibility and FD, periods of soil development can be identified even when too subtle to be observed in cores or exposure profiles, and this sensitivity to stratigraphic variation provides an excellent means of stratigraphic correlation.

Samples were collected in the field from freshly exposed or cleaned profiles or from cores extracted and transported to the laboratory in clear carbonate plastic liners. The individual magnetic samples were collected in numbered and demagnetized, 8-cm^3 plastic cubic containers with lids. The sample interval varied slightly, but averaged 40 per meter. These cubes were pressed by hand or driven with a rubber-coated, dead-blow hammer into the exposure or core to

obtain the required amount of sediment. In the laboratory, the cubes were cleaned, sorted, air dried, weighed, and placed in wooden trays prior to measurement.

Susceptibility and FD measurements were obtained using a Bartington magnetic measurement system consisting of a Model MS2 susceptibility meter and a 36mm-cavity, dual-frequency sensor (MS2B). As each sample was measured, data were entered into a database program (Microsoft Excel) for subsequent analysis. Specifics of the measurement procedures are presented in Bartington literature provided with the instrumentation package (Bartington Instruments 1995) and in Gale and Hoare (1991).

Stable isotope (carbon) ratio analysis.

There are few quantitative techniques in use today for paleoecological reconstructions in terrestrial depositional systems. One approach to quantitative reconstructions is to estimate the proportion of C_3 (mesic, cool-season) to C_4 (xeric, warm-season) plants once present at a site using carbon isotopes from humates contained within loess and intercalated soils.

Carbon isotope fractionation occurs during photosynthesis (Smith and Epstein, 1971), and fixation of carbon by plants proceeds along one of three pathways C_3 (Calvin-Benson), C_4 (Hatch-Slack), and CAM (Crassulacean). The latter is not relevant, as it is a desert adaptation which uses both photosynthetic pathways. The carbon isotopic composition ($^{13}C/^{12}C$) of the plant material is highly correlated with the type of photosynthetic pathway followed by the plant (Deines, 1980). Further, vascular plants segregate into two groups on the basis of their isotopic composition, or $\delta^{13}C$ value. C_4 plants (warm, dry-adapted plants) have an average $\delta^{13}C$ value of -14‰, while C_3 plants (cool, moist season plants) average -27 ‰ (Deines 1980; Krishnamurthy et al. 1982).

The isotopic data are expressed as the difference, or delta value (δ), between the sample or standard. The δ value for a carbon isotope in soil is defined as

$$\delta^{13}C \text{ soil} = (\delta^{13}C_{C4})(x) + (\delta^{13}C_{C3})(1-x),$$

where $\delta^{13}C_{C4}$ is the average of $\delta^{13}C$ values of C_4 plants (-13‰), ($\delta^{13}C_{C4}$) is the average of $\delta^{13}C$ values of C_3 plants (-27‰), and x is the proportion of carbon from C_4 plant sources. Isotopic composition of soil organic matter is a direct indicator of the fraction of the biomass using the C_3 or C_4 photosynthetic pathways. Paleosol humus probably represents organic matter from the last few hundred years before burial, given the short residence times typical for humus in most modern soils (Birkeland 1984).

Analyses have been performed on pedogenic carbonate (Cerling 1984; Cerling and Hays 1986; Cerling et al. 1989; Gu et al. 1991; Humphrey and Ferring 1994), lacustrine carbonate (Humphrey and Ferring 1994), on alluvial and eolian sediments (Jasper and Gagosian 1989; Lin et al. 1991); Aucour et al. 1994; Nordt et al. 1994), on soil organic matter (Krishnamurthy et al. 1982, 1995; DeLaune 1986; Schwartz et al. 1986; Guillet et al. 1988; Schwartz 1988; Ambrose and Sikes 1991), and on opal phytoliths (Kelley et al. 1991; Fredlund 1993).

The procedure utilized is similar to that used by our laboratory for the preparation of soil and sediment samples for radiocarbon humate dating, which renders the results compatible with those obtained in the course of age correction for the effects of isotopic fractionation (Johnson and Valastro 1994). Samples of 300-400 grams were collected from the cores or exposures of the study sites and were prepared by first disaggregation in 4-liter beakers filled with distilled water. They were then skimmed with a 60-mesh screen to remove floating organic debris. Next, the samples were washed through a 230-mesh screen with distilled water into a second beaker in order to remove the sand and coarse silt fractions; the fine fraction remaining is assumed to contain the adhering organic carbon. The samples were then treated with concentrated HCl in order to remove the inorganic carbon contained within the carbonate. This step is particularly important because of the prevalence of limestone bedrock in the Fort Riley area. Following distilled water washes and oven-drying (100°C) in 4-liter beakers, the samples were pulverized and packaged. They were then submitted to Geochron Laboratories for stable carbon isotope ratio analysis.

Biogenic opal analysis.

The objective of this research was to recover fossil opal phytoliths (siliceous plant cells) from sediment and soil samples collected at the study sites in order to provide a means of stratigraphic correlation and to reconstruct the vegetative history for the reservation. Phytoliths are the most common biosilicate in the alluvial fill deposits. Sponge spicules, another form of biogenic silica, may also be present but are much less common and of limited use when compared to the potential of phytoliths. The biogenic signature offers and excellent means of stratigraphic correlation, particularly in the identification of the Pleistocene-Holocene boundary, i.e., the end of the Last Ice Age about 10,000 years ago.

Grass opal phytoliths are the best studied and can be separated into morphologic categories related to the plant photosynthetic pathways and the major subfamilies of grasses. Twiss and his students (Twiss 1980, 1983, 1987; Twiss et al. 1969; Kurmann 1981, 1985) were the first to recognize the correlation between grass photosynthetic groups (adaptations) and phytolith morphology, i.e., the major subfamilies of grasses correspond to three morphologic classes of phytoliths.

Most Poaceae (grasses) employ the C_3 pathway (Calvin) for the fixation of CO_2 in the photosynthetic process. Commonly, these grasses belong to the Pooideae (festicoid) subfamily. Grasses included in this subfamily include the bromes (*Bromus* spp.), fescues (*Festuca* spp.), needlegrass (*Stipa* spp.), wheatgrass (*Agropyron* spp.), bluegrasses (*Poa* spp.), and many cereals such as rye (*Secale cereale*), oats (*Avena* spp.), barley (*Hordeum vulgare*), and wheat (*Thriticum aestivum*). The C_3 grasses are widespread but are best adapted to the higher (cooler) latitudes and altitudes.

Conversely, the C_4 grasses, employing the Hatch-Slack CO_2 photosynthetic pathway, are most successful in the lower (warmer) latitudes and altitudes. This system is better adapted to high temperatures and low moisture conditions. In the Great Plains, two

groups (subfamilies) of grasses typically utilize the C_4 pathway, the Chloridoideae and Panicoideae subfamilies. Examples of grasses within the Chloridoideae subfamily are the three-awns (*Aristida* spp.), gramas (*Bouteloua* spp.), buffalo grass (*Buchloe dactyloides*), saltgrasses (*Distichlis* spp.), sandreed grass (*Calomovilfa* spp.), lovegrasses (*Eragrostis* spp.), muhly grasses (*Muhlenbergia* spp.), and dropseed grasses (*Sporabolus* spp.). Although the Panicoids are well adapted to high temperatures, they require more moisture than the Chloridoids, and are consequently better adapted to the eastern Great Plains, e.g., eastern Kansas. Included in the Panicoids are the bluestems (*Andropogon* spp.), panicums (*Panicum* spp.), indian grass (*Sorgastrum nutans*), gama grass (*Tripsacum dactyloides*), and the cereal grasses corn (*Zea mays*) and sorghum (*Sorghum halepense*).

Opal phytoliths are generally well preserved in most sediment and can be isolated from sediment samples and analyzed to reconstruct the paleoenvironment for a particular area. This has been successful on a number of sediment types, including loessal sites in China (Lu et al. 1991), Nebraska (e.g., Fredlund et al. 1985; Bozarth 1991b, 1992b; Johnson et al. 1993a; Fredlund 1993) and the Southern High Plains (Bozarth 1995), as well as alluvium in Kansas (Kurmann 1981, 1985; Bozarth, 1986) and the Southern High Plains (Bozarth 1995), and swamp and upland sediment in Panama (Piperno 1988).

Samples were collected from cores and exposures, using a trowel cleaned thoroughly between samples. Samples were placed in sterile plastic bags for storage until extraction. Phytoliths were isolated from 5-gram subsamples using a procedure based on heavy-liquid (zinc bromide) flotation and centrifugation (Bozarth 1991). This procedure consists of five basic steps: 1) removal of carbonates with dilute hydrochloric acid; 2) removal of colloidal organics, clays, and very fine silts by deflocculation with sodium pyrophosphate, centrifugation, and decantation through a 7-micron filter; 3) oxidation of sample to remove organics; 4) heavy-liquid flotation of phytoliths from the heavier clastic mineral fraction using zinc bromide concentrated to a specific gravity of 2.3; 5) washing and dehydration of phytoliths with butanol; and 6) dry storage in 1-dram glass vials.

A representative portion of each phytolith isolate was mounted on a microscope slide in immersion oil under a 22x40 mm cover glass and sealed with clear nail lacquer. Each isolate was then studied at 400x with a research-grade Zeiss microscope. Each sample slide was first examined to determine the quality of preservation of the phytoliths. At least 200 phytoliths, were counted in all of the samples with adequate preservation. A complete slide was scanned and all phytoliths classified in those samples with poor preservation.

Estimates of phytolith concentration were made using an indirect method reported by Piperno (1988). A known number of exotic spores (in this case *Lycopodium*) were added to each sample after the oxidation stage. The concentration of phytoliths (per gram) was computed as follows:

Phytolith conc. = no. of phytoliths counted x (total no. exotics added / no. exotics counted) / 5

Concentration permits an evaluation of the phytolith production, preservation, and sedimentation rate for a given sample interval.

Phytoliths were classified according to a convention that has been developed and used by other reports and publications. An extensive reference collection of plants native to the Great Plains has been developed in the KU Palynology Laboratory through field collection, research plots, solicited samples, and specimens supplied by the University of Kansas Herbarium.

Results and Discussion

The primary source of correlation information was the radiocarbon database (Table 3.1). Forty-four age determinations were used to ascertain the ages of buried soils and in two instances the age of charcoal from a buried hearth and a bison bone associated with another buried hearth. Reservation wide, over 130 radiocarbon ages were obtained for purposes of stratigraphic correlation. In addition, examples of application of rock magnetic, stable carbon isotope ratio, and biogenic opal analyses are presented below for Forsyth and Wildcat Creek systems.

Table 3.1. Valley (Alluvial) Radiocarbon Ages–Wildcat and Forsyth Creeks

Site No.	Depth (cm)	ISGS No.	Uncorrected Age	δ^{13} (0/00)	Corrected Age
<u>WILDCAT CREEK</u>					
WC1 (FR7)	85	3780	1,790±70	-16.7	1,920±70
	226	3781	9,830±100	-17.0	9,960±100
	315	3604	17,000±300	-22.7	17,040±300
	434	3603	23,770±300	-19.2	23,860±300
	560	3608	23,780±410	-18.6	23,890±410
	612	3607	23,400±400	-19.2	23,500±400
WC4-T1	149	4001	2,710±70	-16.3	2,850±70
	222	4024	1,850±70	-19.3	1,940±70
WC4-T2	117	4073	3,370±70	-15.9	3,520±70
	175	4000	4,210±70	-18.6	4,310±70
	271	4025	5,440±70	-16.7	5,570±70
WC4-T3	113	4171	1,260±70	-18.0	1,380±70
WC5-T1	126	3998	1,600±70	-16.4	1,740±70
WC5-T2	322	4072	24,280±150	-16.9	24,410±150
WC5-T6	88	4172	3,480±70	-13.9	3,660±70
	359	4034	10,150±80	-16.0	10,290±80

FORSYTH CREEK					
FR4A	86	3856	1,720±70	-15.7	1,870±70
	118	3617	2,850±70	-17.1	2,980±70
	380	3609	6,630±70	-17.7	6,740±70
FR4B	155	3871	8,510±90	-17.0	8,640±90
	167	3860	8,550±70	-17.5	8,680±70
	225	9090[2]	9,600±70	-19.6	9,690±70
	264	3778	10,600±200	-19.2	10,690±200
	270	3858	10,520±140	-19.8	10,600±140
	320	9091[2]	10,230±60	-17.4	10,350±60
	375	3857	10,410±120	-17.5	10,530±120h[3]
	380	3605	4,120±70	-10.5	4,350±70
	537	3953	10,520±80	-18.2	10,630±80
FC1-T1	160	4038	1,200±70	-18.7	1,300±70
FC2-T1	145	4035	2,470±70	-18.2	2,580±70
	259	4042	2,800±70	-16.2	2,950±70
FC3-T1	147	4039	4,770±70	-14.9	4,940±70
FC3-T2	193	4074	8,260±90	-16.7	8,400±90
FC4-T1	140	4066	6,410±90	-15.2	6,570±90
FC5-T1	167	4062	4,860±70	-13.6	5,040±70
	186	4179	5,810±70	-15.0	5,970±70
FC5-T2	100	4061	4,910±70	-14.9	5,080±70
	208	4068	9,310±90	-17.1	9,430±90
	295	4063	12,760±100	-21.0	12,830±100
FC6-T2	120	4065	5,070±70	-14.1	5,250±70
	188	4067	6,770±110	-15.8	6,920±110
	208	4057	5,670±70	-25.8	5,660±70
	208	4058	6,880±80	-19.2	6,970±80
	280	4060	10,600±160	-18.0	10,710±160

Forsyth Creek.

Radiocarbon ages from Forsyth Creek range from about 1,300 years B.P. (before present) to as old as about 12,800 years B.P., with remaining ages distributed throughout the last 10,000 years. Since all ages were from buried soils or hearths associated with the soils, the ages can be construed as times of flood-plain stability. From the temporal distribution of the ages, stability appears to have occurred at about 1,300, 1,900, 2,600-3,000, 4,400, 5,000-6,000, 6,600-7,000, 8,400-8,700, 9,400-11,000, and about 13,000 years B.P. Hearths, roasting pits, middens (human debris), and debitage (lithic debris) were found in association with most of the soil-forming periods (major exception: c. 13,000 year-old surface), indicating widespread human occupancy of the riverine

surfaces during the last 10,000 years of more. The relationship between the fills of the T2 and T1 surfaces (terraces) at site FR4, near the confluence with Threemile Creek, is depicted in Figure 3.7.

Rock magnetic parameters provided characteristic signatures for the various fill units. Data from site FR4 illustrate the magnetic response to variations in the nature of the terrace fills. Susceptibility from T2 fill reflects the soil-forming and stable periods within the stratigraphy (Figure 3.8). Buried soils are indicated by the "Ab" notation. Susceptibility is weak for the 3, 4, and 5Ab soils because of dilution by organic matter. Swells in the Frequency dependence curve indicate much better the well-developed nature of the buried soils. The well developed 2Ab within the T1 fill is clearly expressed magnetically (Figure 3.9), but the spike created by fire associated with the hearth is remarkable but yet commonplace in many of the fills.

The biogenic opal signal from T2 fill at site FR4 illustrates the signature characteristic of the end of the Last Ice Age and the early part of the Holocene (Figure 3.10). Composition of the riparian tree community consisted of conifers (e.g., spruce) and deciduous varieties until about 8,600 years B.P., when the deciduous species begin to dominate, as evidenced by the "spiny spheres" and *Celtis* sp. (Hackberry) phytoliths. The notable peak in Chloridoideae types at about 9,000 years B.P. is a benchmark feature in the regional phytolith record.

Wildcat Creek.

Radiocarbon ages from buried soils begin about 1,300 years B.P. (as with Forsyth Creek), but the oldest ages ranged up to about 24,000 years B.P., with these oldest ages coming from a large, well-preserved alluvial fan situated in the lower part of the system. The fan was one of those that had survived the system-wide entrenchment about 10,000 years ago. From the temporal distribution of the ages in this valley fill, stability appears to have occurred at about 1,300, 1,700-1,900, 2,800-3,000, 3,500-3,700, 4,400, 5,600, 10,000, 17,000, and 23,000-25,000 years B.P. With the exception of the pre-10,000 ages, these periods of stability are essentially the same as those in Forsyth Creek, indicating synchronous regional change in the systems; this synchroneity reflects a climatic forcing. As with Forsyth Creek and other systems in the basin, cultural remains such as hearths, roasting pits, middens (human debris), and debitage (lithic debris) were found in association with most of the soil-forming periods (major exceptions: c. 17,000 and 23,000-25,000 year-old surfaces), again indicating widespread human occupancy of the riverine surfaces during the last 10,000 years of more.

Rock magnetic parameters provided signature curves for the fills in the Wildcat Creek system as well. The large alluvial fan in the low part of the main valley (Site WC1) yielded basal radiocarbon ages of about 24,000 to 17,000 years B.P. and an age of 1,900 years B.P. on the uppermost buried soil (Table 3.1). Magnetic data from WC1-T1 (Figure 3.11) illustrate the buried soil development. Soil 2Ab has a weak signal because it has undergone degradation as a result of the surface "welding" to it. The 3Ab represents a regionally expressed soil that developed at the Late Pleistocene - Holocene boundary both on the uplands and in valleys. The soil has an unusually well-developed B horizon

as evidenced by the high response in the frequency dependence curve. The soils at 17,000 and below are poorly expressed due to reduction of the ferromagnetic minerals by groundwater and to the vacillation in sediment size within this facies change zone of the fan and stream deposits. Although undated, buried soils expressed in the magnetic curve from site WC1-T2 most likely date to about 1,300 and 1,900 years B.P. (2Ab and 3Ab, respectively), based on dated curves from corresponding fill elsewhere (Figure 3.12). A third example of the magnetic signatures and ages is site WC4-T2 (Figure 3.13). The lower two soils are poorly developed (4Ab and 3Ab), whereas the 2Ab is even better developed that the surface soil, which has welded to it. The inferred age of the 2Ab is approximately 3,500 years B.P.

Interpretation and Model Validation

Cultures of the central Great Plains have been divided into seven broad categories, each of which has been temporally defined (Table 3.2). One cultural period that had been surprisingly well-represented in the fill stratigraphy, despite its antiquity, is the Early and Middle Archaic Period; hearths and other remains have been discovered in the 3 to 4-m depth range. Whereas more recent material, also very common, is buried stratigraphically above or within younger fills.

Table 3.2. Central Great Plains Cultural Chronology

Paleoindian	11,600 - 9000 BP 9,650 - 7050 BC
Early-Middle Archaic	9000 - 5000 BP 7050 - 3050 BC
Late Archaic	5000 - 2,000 BP 3050 - 50 BC
Early-Middle Woodland	2,000 - 1,500 BP 0 BC - AD 450
Late Woodland, Late Prehistoric, and Protohistoric	1,500 - 250 BP AD 250 - 1700

Forsyth Creek

<u>*Alluvial landforms: spatial patterns*</u>.

Five different alluvial surfaces appear in the Forsyth drainage, and, with one exception, these are regularly distributed along the main valley (Figure 3.14). T0 is developed to a small extent throughout, but T1 and T2 clearly dominate, with four distinct, large areas of coalescing fans. The largest area of T0 is located at the confluence of the two branches forming the main valley, a network position where such channel mobility is anticipated (Figure 3.15). The Williston Point area, another valley confluence, still retains large terrace remnants, in particular the triangular-shaped unit of T2 wedged between the main channel and the tributary (Figure 3.16). The largest terrace remnants

are found in lower Forsyth Creek, at its confluence with Threemile Creek (Figure 3.17), where all five alluvial units appear.

Sixteen sites were investigated via backhoe trenching in the Forsyth Creek valley. FR 4, a T2 site at the confluence, produced radiocarbon age ranges about 11,000 to 8,000 yr B.P., whereas FC6-T2, a site in that same area, produced ages from about 11,000 to 5,200 yr B.P. (Table 3.1). The existence of an older uppermost age at the former site may be due to the stripping ($\leq$ 1m) taking place during development of the power line corridor, i.e., the younger buried soil was mechanically removed. Four T2 sites in the Williston Point area indicated fill ages that range from about 5,000 to 12,000 yr B.P., as does T2 site FC4-T1 upstream. T2 fill ranges in age from over 12,000 to about 5,000 yr B.P. T1 fill was dated at three sites, FR4, FC1-T1, and FC2-T1, all of which indicate ages less than 5,000 to about 1,000 yr B.P. The older age of 6,740 years B.P. represents a basal buried soil.

Upper and lower Forsyth Creek is dominated by T2 fill and large alluvial fans (Figure 3.18). The large body of T2 fill in lower Forsyth Creek (at its confluence with Threemile Creek) contains, evidence of an apparent heavy concentration of late Paleoindian and early Archaic cultural activity. This large confluence location would have provided a major resourse for the early peoples: availability of game, fish, firewood, building materials, etc. Similarly, today it is used heavily in military activities and by visitors.

Alluvial landforms: chronological patterns.

In order to develop a detailed rendering of the fill stratigraphy, with regard to buried soil continuity, selected areas of valley were subjected to high-resolution coring on a grid system. Data indicated that, for these reaches, the buried soils were continuous and displayed little topographic variation. For Forsyth Creek, the area of confluence with Threemile Creek was investigated (Figure 3.19). The 3-D block rendering of this area displays the major buried soils and major archaeological material encountered (hearths and bison bone) (Figure 3.20).

Potential distribution of subsurface cultural materials.

The relative area of flood plain is a small part of the total valley fill (Figure 3.21), providing a limited area for Late Prehistoric and Protohistoric. A sizable area is involved in the T1 and T2 fill distributions, particularly the latter (Figures 3.22, 3.23). The large area of T2 fill at the confluence with Threemile Creek, dating to Paleoindian and Archaic, very likely contains buried cultural material and sites due to its resource-rich location. A similar confluence area in lower Sevenmile Creek, containing a large expanse of T2 fill, produced Early Archaic hearths in three of four backhoe trenches. T3 fill should have only surficial cultural material, and that small remnant has been heavily modified by road construction (Figure 3.24). Although undated in Forsyth Creek, the alluvial fan fill appears, from color and stratigraphic position, to be ages similar to those in Wildcat Creek where temporal determinations have been made, i.e., pre-Paleoindian to Woodland (Figure 3.25). Table 3.3. summarizes the association between different fill units and the age range of potential buried cultural material.

Wildcat Creek

Alluvial landforms: spatial patterns.

The strange, incomplete appearance of the pattern of alluvial fills in Wildcat Creek is a function of adherence to the base boundary extending down the valley axis (Figure 3.26). Even with this incomplete mapping, the dominance of the T2 in the main valley is obvious: T0 and T2 are poorly developed throughout the mapped reach (and beyond). The pattern of T1 fill indicates that a limited amount of lateral migration occurred then, prior to entrenchment to the present level. The recent nature of the entrenchment is apparent: although the channel is highly meandering and characterized by actively eroding cutbanks, little of the T1 and adjacent T2 has been removed. Coalescing fans are common, especially in the upper reaches of the main valley (Figure 3.27). In fact, fans dominate the Little Arkansas Creek; due to the coarse and active nature of the fans, the channel has, in one area, occupied a straight course for a long time, i.e., no terrace fill has been deposited (Figure 3.28). The valley bottom in the lowermost part of the valley appear as a series of stair steps: T0, T1, T2, and fan deposits are all in close proximity to one another and have distinct scarps at their contacts (Figure 3.29).

Table 3.3. Buried Cultural Associations and Estimated Ages[1] for Alluvial Fills

Fill	Forsyth Creek	Wildcat Creek
T0	*Late Prehistoric - Protohistoric*	*Late Prehistoric - Protohistoric*
T1	*Late Archaic - Late Woodland*	*Late Archaic - Late Woodland*
T2	*Paleoindian - Middle Archaic*	*Paleoindian - Late Archaic*
Fans	*Paleoindian - Early Woodland*	*Paleoindian - Early Woodland*

[1] from ^{14}C ages and other stratigraphic data

Wildcat Creek is split into four separate 3-D relief images (Figure 3.30). Upper Wildcat Creek is dominated by alluvial fans and by T2 fill (Figure 3.31). The alluvial fans have determined the course of the meander plain by serving to deflect the channel toward the opposite valley wall. The Little Arkansas Creek also has been dominated and controlled by alluvial fan development and growth, a process that has probably persisted for the last 20,000 years or more, as evidenced from the radiocarbon ages determined from fan fill (Figure 3.31). The middle reach of Wildcat Creek is similarly dominated by T2 fill and to a lesser extent by alluvial fans, as is the lower part of Wildcat Creek (Figure 3.32).

Alluvial landforms: chronological patterns.

Two areas in Wildcat Creek were examined via coring in a high-resolution grid: a confluence area where the valley widens and contains a large alluvial fan in the upper part of the main valley (Figure 3.33) and an area downstream where a variety of fills and associated surfaces exist in close quarters with a large alluvial fan (Figure 3.34). The block diagram from upper Wildcat Creek illustrates the complex, but yet predictable pattern of the buried soil distribution within this small area (Figure 3.35). This morphostratigraphic relationship generally prevails throughout the Wildcat system, as is evidenced by the diagram from lower Wildcat Creek (Figure 3.36).

Potential distribution of subsurface cultural materials.

Due to recent, region-wide entrenchment, Wildcat Creek has little expression of flood plain (Figure 3.37), but older fills abound. T1 surfaces and fills are common throughout, including the Little Arkansas Creek valley (Figure 3.38). T2 fills are, however, ubiquitous, implying that a large potential exists for the presence of buried Paleoindian and Archaic materials in the main valley (Figure 3.39). Because of the relatively large extent and age range of alluvial fans in the creek system valley, it is also likely that potential sites are buried in these deposits as well; in fact, the higher and better drained fans may have been preferred surfaces during times of frequent valley flooding (Figure 3.40). Table 3.3 summarizes the association between different fill units and the age range of potential buried cultural material.

Model Comparison

Computer simulations generated by the CHILD landscape evolution model simulate erosion and sedimentation in a very realistic pattern and, when applied to Fort Riley, provide an extremely accurate and proportional rendition of reality. According to the simulation, elevations of the T2 and T1 terraces are 9-8m and 6m, respectively; both of these values are remarkably close to actual mean elevations. Despite the narrow nature of the stream valleys on Fort Riley, a relatively large area of the valley bottom exists as T2 terrace and associated fill. A perspective view of the topography of the modeled meander belt (Figure 4.10) exhibits large areas of T2 terrace (red-orange color) and provides a pattern that very closely mimics the real world. A similar pattern is apparent in the plan view of model output for the present day (Figure 4.11).

Although it is crucial that the model simulation generate a significant proportion of T2 terrace area in the valley, that is only the first step in approaching reality. The critical test for the model simulation is that of differentiating the age of the fills beneath the T2 and T1 terraces. The model has successfully accomplished this in that it has designated appropriately-aged fill beneath these two different surfaces. The A3 and B2 surfaces in Figure 4.13 (yellow) represent the T2 terrace, whereas the A2 and other orange bodies are analogous to the T1 terrace.

CHAPTER 4
Transferability of the 3D Modeling Approach

by
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Model Transferability

Having demonstrated the utility of the CHILD simulation tool for predictive modeling of buried archaeological site localities in a fluvial environment in the eastern Kansas Plains, brief consideration can now be given the inherent *transferability* of the approach to other geomorphic environments and land management contexts. It is important to emphasize at the outset that the CHILD model was not developed for exclusive application to the Fort Riley case study discussed in the previous chapters. To the extent that there is a recognized commonality between the architecture of fluvial systems and the complex interrelationship of hillslope and channel processes, the CHILD model is applicable to a broad range of landforms and fluvial environments. To quote the model's developers (Tucker et al. 1999:1; emphasis added) on the broad applicability of their simulation tool:

> Understanding the dynamics of landscape evolution is a challenging problem, for two reasons. First, the processes involved are inherently destructive, and therefore the geologic record of landscape development is usually fragmentary. Second, the sculpture of terrain involves a fascinating but complex set of interacting nonlinear processes, and the complexity of the drainage basin "system" often defies intuitive understanding. While challenging, however, the problem is not intractable. Information on landscape history is still preserved in the form of topography itself, and often also in the form of associated sedimentary deposits such as alluvial valley fills. And despite the complexity of geomorphic processes and their interactions, *the resultant landforms often exhibit an underlying similarity even under varying geologic and climatic settings.*

With this in mind, then, "the CHILD model is designed to simulate the evolution of fluvially-dominated landscapes formed chiefly by physical erosion (thus, it does not include glacial erosion or karst development, for example)" (ibid.:2). Any such landscape can be subjected to study, provided that the proper data requirements are met and that scaling issues are adequately accommodated. Indeed, the long-term goal of model development was the creation of "a general 'programmer's toolkit' for many different

types of environmental modeling applications" in a variety of landscapes and at a variety of time scales (ibid.).

For the federal land-managing agency concerned both with land-use impacts to the landscape and with the protection and stewardship of resources on (or buried within) that landscape, the practical utility of a geomorphological simulation tool such as CHILD cannot be overemphasized. This managerial utility has only begun to be explored fairly recently (see, for example, McGregor and Thompson 1995; Doe 1999a, 1999b), but has important implications for proactive land-use planning and land management practices, especially in cases where land-use practices are intensive and inherently destructive (e.g., military training exercises). The essential value of geomorphological simulation modeling over its alternatives was articulated some years ago in the following terms:

> The use of a theoretically based simulation model can greatly improve our understanding of the physical system, highlighting properties of the system which should be predictable but which, given the complexity of the real world, only become apparent using such a model. Whilst we may be able to write theoretical statement to describe the operation of the system, once we have more than two parameters to consider, we cannot mentally imagine their combined effect on model output...Nor can field research necessarily be much help, since extensive, controlled experiments in the field are prohibitively expensive, and may be rendered impossible by uncontrollable climatic variations. Even using a simple simulation model, we can systematically improve our understanding of complex environmental systems in ways which have not been previously possible (Kirkby et al. 1993:150-151.)

We believe that the CHILD model affords both researchers and land-managers alike a powerful tool for the study of landscape evolution, especially with respect to its applicability at longer geologic time scales than is normally the case with landscape evolution models. Its ability to track such things as *time of deposition* and *exposure age* for individual stratigraphic layers has enormous potential for alluvial geoarchaeology and 3-D predictive archaeological modeling.

In a similar fashion, the empirical geomorphological and geoarchaeological testing carried out at Fort Riley, Kansas, as a complement to the simulation modeling is also inherently transferable to other environmental and geomorphic settings. This research has resulted in a high-resolution landscape model that represents the relative and absolute age of soils and sediments associated with the different landscape elements, e.g., flood plains, alluvial terraces, alluvial fans, colluvial slopes, and ridge tops. Complexity is introduced by the fact that the age of these individual elements is not the same at all locations, but yet systematic patterns have emerged.

The experience of developing the geoarchaeological model for Fort Riley has provided the appropriate strategy and technological definition for extracting a similar level of resolution from study areas for which little or no baseline information on landform distribution and age exist. This approach may be described as a combination of *chronostratigraphy* and *morphostratigraphy*, i.e., the individual landforms are assessed

for their surface and subsurface ages, and then similar forms (morphologies) are assigned similar ages. For example, an alluvial terrace, once identified, would be dated relative to other landforms and then in an absolute fashion from the surface downward using the appropriate techniques, such as radiocarbon dating.

A sequence of steps would be initiated when gathering the necessary information for landscape modeling in an unfamiliar study area. Landforms would first be mapped, preferably in a GIS, using available topographic and geologic maps, aerial photography, and ground reconnaissance. These map data would then utilized to develop a relative age differentiation, usually a fairly simple task for the trained earth scientist/geomorphologist. The process then focuses on the limited amount of fieldwork necessary for model development: using the GIS database and other appropriate sources, study sites are selected from within the various landform categories. Landform categories are sampled in their natural hierarchy, e.g., flood plains of lower order systems (small tributaries) to those of higher orders (large streams or rivers). After sample sites have been selected, the soils and sediments (stratigraphy) are described and samples collected for age determination. Once absolute age determinations have been obtained, the morphostratigraphy, or the association between the landform and the age of associated sediments is then defined and mapped in the GIS database. Resulting data can then be used as input for computer-based landscape evolution models such as CHILD. The GIS software (e.g., ArcINFO and ArcView) computes the necessary input databases, such as coordinates/distribution, percent total area, and age distribution of the various landforms. Further, the GIS software can be employed to generate probabilities for surface and subsurface expression of the remains from various prehistoric cultures and cultural periods, thereby providing necessary cultural resources management information. The approach is simple, accurate, and time and cost efficient. Moreover, it is transferable to all geomorphic, or landscape environments, regardless of complexity. This has clearly been demonstrated for the Fort Riley case study presented in the previous chapters. We now turn to another potential case study from northern New Mexico.

Los Alamos, NM, Case Study: Feasibility of Applying the 3D Approach

This section discusses the feasibility of applying the CHILD model for purposes of 3-dimensinal predictive modeling of buried archeological sites at Los Alamos National Laboratory (LANL), New Mexico. Can the model be used for assessing the risks of inadvertent discovery involved in planning future activities, forest fire recovery, as well as assessing the risks involved in daily routine maintenance operations at the Laboratory? After a brief overview of the prehistory of the Pajarito Plateau, discussion centers on the land management challenges confronting the Laboratory. This is followed by a discussion of data sources required to support the CHILD model, and finally the potential for technology demonstration will be assessed.

Los Alamos National Laboratory is located on the Pajarito Plateau in northern New Mexico (Figure 4.1) The plateau is made up of a series of finger-like mesas that represent the incised and eroded pyroclastic apron emplaced by a series of Miocene to

Pleistocene age (25-1.1 mya) volcanic eruptions emanating from the Valles Caldera in the Sierra de los Valles of the Jemez Mountains (LASL 1976). The Jemez mountains and the Pajarito Plateau are located directly west of the Rio Grande Rift that is approximately 60 km wide at this point and includes the Espanola Valley and the Sangre de Cristo mountains to the east. LANL covers 43 m^2 of the plateau and shares contiguous borders with the Los Alamos townsite, San Ildefonso Pueblo, White Rock townsite, Bandalier National Monument and the Jemez mountain watershed that is managed by the U. S. Forest Service.

The cultural history of the Pajarito Plateau is varied and complex. The plateau has been occupied intermittently for the past 10,000 years until the intensive ancestral Pueblo occupation beginning in the Coalition Period at A.D. 1200. The prehistoric and early historic sequence has been summarized by Vierra and Hoagland (LANL 2000) as follows:

PALEO-INDIAN PERIOD: 10,000 to 5,500 B.C.

Small groups of Paleo-Indian hunter-gatherers may have followed bison herds up and down the Rio Grande, with trips onto the Pajarito Plateau to procure obsidian and other subsistence resources. This period is represented on Los Alamos National Laboratory (LANL) land by a Folsom point found by Steen (1977:7) on a mesa north of Ancho Canyon. Clovis, Folsom, and Planview points have also been identifed at other locations on the Plateau (Acklen 1993, 1997; Lent et al. 1986; Traylor et al. 1990; Wiseman 1992). Obsidian obtained from Jemez Mountain sources has been found on Paleoindian sites located as far away as northern Colorado (Wilmsen 1974:114).

ARCHAIC PERIOD: 5,500 B.C. to A.D. 600

Archaic hunter-gatherer groups relied on a variety of small game and plant species, while hunting with the spear and atlatl. Piñon-juniper woodlands on LANL land contain evidence of these temporary campsites as scatters of obsidian tools, chipping debris and diagnostic projectile points (e.g., Biella 1992; Moore et al. 1998; Winter and Baker 1981). These sites presumably reflect the seasonal use of upland settings during the fall for piñon nut collecting, hunting and lithic procurement activities. Winter sites with structures have been excavated at lower elevations near Otowi at the Rio Grande (Lent 1991) and at Abiquiu Reservoir (Stiger 1986). The Late Archaic continues the hunting and gathering pattern with the addition of maize cultivation to the subsistence base. Maize has been directly dated to 2440 ± 250 B.P. (uncorrected; M-466; Crane and Griffen 1958) and 2410 ± 360 B.P. (Arizona; Long in Ford 1985) at Jemez Cave located in the Jemez Mountains near Soda Dam at Highway 4.

EARLY DEVELOPMENTAL PERIOD: A.D. 600 to 900

Maize horticulturists who lived in semi-subterranean pithouses characterized the early Developmental period. They began to make painted pottery with simple designs (e.g., Lino Gray or Kana'a Gray), and used the bow and arrow. Most habitation sites are

located at lower elevations near the Rio Grande, with the Plateau continuing to be used on a seasonal basis. There is no archaeological evidence for this period at LANL.

LATE DEVELOPMENTAL PERIOD: A.D. 900 to 1200

Late Developmental horticulturists still relied to a great extent on hunting and gathering. Pithouses persisted in some places, but sites are typically small adobe masonry structures that are found at wider range of altitudes. Kawhe'e Black-on-white is a mineral painted pottery that is produced during this time period. Indented corrugated wares are used as cooking and storage vessels. Only a few possible pithouse locations and associated artifacts have been identified on LANL land.

Table 4.1 Culture Historical Chronology for the Northern Rio Grande

CULTURE	PERIOD	DATES
Paleoindian	Clovis	9500-9000 B.C.
	Folsom	9000-8000 B.C.
	Late Paleoindian	8000-5500 B.C.
Archaic	Jay	5500-4800 B.C.
	Bajada	4800-3200 B.C
	San Jose	3200-1800 B.C
	Armijo	1800-800 B.C
	En Medio	800 B.C- A.D. 400
	Trujillo	A.D. 400-600
Ancestral Pueblo	Early Developmental	A.D. 600-900
	Late Developmental	A.D. 900-1200
	Coalition	A.D. 1200-1325
	Classic	A.D. 1325-1600
Native American, Hispanic, and Euro-American	Spanish Colonial	A.D. 1600-1821
	Mexican	A.D. 1821-1846
	U.S. Territorial	A.D. 1846-1912
	Statehood to World War II	A.D. 1912-1945
	Recent	A.D. 1945-present

COALITION PERIOD: A.D 1150 to 1325

The Coalition period saw a substantial increase in the number, size, and distribution of above-ground habitation sites, with year-round settlements expanding into upland areas on the Pajarito Plateau. The long-term process of site aggregation begins during this period, with early sites containing adobe and masonry rectangular structures with 10-20 rooms. These small rubble mound sites are the most common at LANL. In contrast, later sites of this period consist of large masonry enclosed plaza pueblos that contain over 100 rooms. The construction of agricultural features such as terraces, gravel mulch gardens, and dams suggest an even greater reliance on horticulture. Most researchers attribute the increase in site density to migration (Wendorf and Reed 1955, Cordell 1979, Hill and Trierweiler 1986; Hill et al. 1996), but others see the increase in site numbers a result of local population growth (Steen 1982). The beginning of the

CoalitionPeriod coincides with the shift from mineral to organic painted pottery, including Santa Fe Black-on-white. Ceramic cooking and storage vessels are mainly produced using a smeared-indented corrugated style.

CLASSIC PERIOD: A.D. 1325 to 1600

The Classic period is characterized by intensive maize agriculture. Ancestral Pueblo settlements on the Pajarito Plateau are aggregated into three population clusters with outlying one-to-two room fieldhouses. The central site cluster consists of four temporally overlapping sites: Tsirege, Navawi, Tsankawi and Otowi. Otowi and Tsirege are located on LANL land. Mera (1935) suggested that the initial occupation of these pueblos had occurred during the 14th century. Tsirege, Tsankawi and Otowi continued to be occupied during the 15th century, with only Tsirege and Tsankawi remaining by the 16th century. Oral traditions at San Ildefonso indicate that Tsankawi was the last of the plateau pueblos to be abandoned. The introduction of glaze-painted ceramics to the south of Frijoles Canyon and the production of Biscuit wares in the northern Rio Grande area mark the beginning of the Classic period. These Biscuit wares include a temporal sequence from Biscuit A (Abiquiu Black-on-gray), Biscuit B (Bandelier Black-on-gray) to Biscuit C (Cuyamungue Black-on-tan). Sankawi Black-on-cream, Potsuwi'i Incised and plainware cooking vessels are also produced during this time period. The latter utility pottery can include micaceous types. The central group of four Classic period ruins are ancestral to the Tewa speakers now living at San Ildefonso Pueblo.

SPANISH COLONIAL PERIOD: A.D. 1600 to 1821

Due to a series of droughts, the plateau was eventually abandoned during the mid-1500s. New pueblos were occupied in the Rio Grande Valley. Although the historic period begins with Coronado's exploratory expedition up the Rio Grande in 1540-1541, most researchers date the period from about A.D. 1600. This date corresponds with Oñate's settlement in New Mexico and imposition of the Spanish ecomienda/estancia system on Rio Grande populations. The Spanish controlled Pueblo pottery production requiring the manufacturing of european vessel forms and taxation jars. These jars were sized to provide specific volumes for grain taxation. They often exhibited a distinctive shoulder at the mid-point of the vessel. Historic ceramic types include Tewa Polychrome, Kapo Gray or Black, and Ogapoge Polychrome. The Pueblo Indians revolted against the Spanish in 1680, with some sites on the Plateau being reoccupied during this refugee period (e.g., Nake'muu).

With the reconquest and resettlement of New Mexico by de Vargas (1693-1696), the economic and settlement systems were completely overhauled (Simmons 1969). The huge mission establishments disappeared as did the estancias of the encomienderos. In their place land was granted to dozens of Hispanic communities and individuals that worked the property themselves. Hundreds of these small land holdings were scattered throughout the Rio Arriba and Rio Abajo.

Athabaskans have been present in northwestern New Mexico since the 15th century; however, the ethnohistorical evidence for Navajos and Jicarilla Apaches in the

northern Rio Grande begins with the Spanish Colonial period (Forbes 1960; Friedlander and Pinyan 1980; Marshall 1995; Marshall and Hogan 1991; Opler 1936, 1971). The Navajos primarily resided in the Gobernador region, but made periodic visits to the Rio Grande valley and Jemez Mountains. The presence of Tewa Polychrome and Jemez obsidian at Pueblito sites attests to these contacts. Some Jicarilla groups wintered in the area of Abiquiu, with seasonal hunting and gathering trips made to the nearby mountains. Two rock rings that could possibly represent the remains of a tipi or wickiup were recorded in Rendija Canyon (Peterson and Nightengale 1993). Test excavations identified the presence of a hearth inside one of the structures that yielded a radiocarbon date of 130±60 B.P. (Beta-58428). This would reflect a calibrated date for the feature within the 18th or 19th centuries. A single obsidian flake was the only artifact recovered. Possible Jicarilla rock ring sites with associated micaceous pottery have been reported for the Rio del Oso valley near Española (Anschuetz per. com. 1999) and at Pecos National Monument (Gunnerson and Gunnerson 1970). Schaasfma (1977, 1992) suggests a possible Navajo affiliation for Piedra Lumbre sites in the Abiquiu area, although Carrillo (1992) considers that some of these sites are associated with local Tewa peoples.

MEXICAN PERIOD: A.D. 1821 to 1846

Mexico declared its independence from Spain in 1821, which brought about a more lenient land grant policy and expansion of the trade network (Levine et al. 1985). Trade between Missouri and Santa Fe along the Santa Fe Trail began soon after independence and dominated events in New Mexico for the next quarter century (Connor and Skaggs 1977). This introduced some comparatively inexpensive Euro-American goods to New Mexico which is reflected in the increase of manufactured items found on sites from this period (Moore 1993).

U.S. TERRITORIAL: A.D. 1846 to 1912

New Mexico remained a part of Mexico until war broke out with the United States. Troops led by Colonel Stephen W. Kearny raised the American flag at Santa Fe and took possession of New Mexico for the United States on August 18, 1846. Grazing and seasonal utilization of the Plateau occurred by non-Indians during the early historic periods, with the first homesteads being established on the Pajarito Plateau during the 1880s (Scurlock 1981:138). New Mexico was provided with a territorial government in 1850, and it remained a territory until it was granted statehood in 1912.

STATEHOOD TO WORLD WAR II PERIOD: A.D. 1912 to 1945

The early 1900s in New Mexico saw a continuation of traditional farming, cattle grazing, timbering and cultural practices. Seasonal homesteading continued on the Plateau, though mostly as a supplement to established year-round residences. Hispanic and Anglo homestead era sites are characterized by wooden cabin and corral structures, rock or concrete cisterns, and a scattering of debris associated with household and farming/grazing activities. In discussing the homestead occupation of current LANL lands it is noted that nearly all of the evidence for homesteading dates to the period of 1912-1945, likely reflecting response to the Enlarged Homestead Act of 1909 and the

Grazing Homestead Act of 1916 (Scurlock 1981). Greater railroad and automobile use allowed for an increase in commerce and tourism, and by the 1940s, New Mexicans began to leave the village rural life for jobs in the larger cities, such as Albuquerque, or for jobs outside the state (Simmons 1993:182).

In 1942, Franklin D. Roosevelt gave the approval to develop the world's first atomic bomb. Because of its isolated location, Los Alamos, New Mexico, was selected as the site of the bomb's design and construction. This project came to be known as Project Y, a subset of the Manhattan Project. The creation of a modern town in Los Alamos influenced surrounding communities in Northern New Mexico. Lands owned by the Los Alamos Ranch School and mostly Hispanic homesteaders were appropriated for use by the Manhattan Project in 1942, thus effectively ending the homesteading era on the Pajarito Plateau (LANL 1997).

Cultural Resources Management Challenges

Due to the dissected nature of the Pajarito Plateau, areas suitable for residential occupation are limited to the mesa tops. Canyon bottoms are subject to seasonal flooding, and were used prehistorically for farming. This pattern of residential occupation of the mesa tops and seasonal use of the canyon bottoms has been maintained to the present. LANL facilities are distributed along the mesa tops with only a few experimental areas located in the canyon bottoms. This pattern is necessitated by the nature of the activities at the Laboratory and the necessity to contain contaminant potential release sites (PRS) to laboratory land. Given the close proximity of residential communities around the Laboratory (San Ildefonso Pueblo, White Rock and Los Alamos), the movement of contaminated sediments off laboratory land is a major concern. However the similarity in residence patterns over the past 1000 years on the plateau has constrained land use flexibility for the Laboratory. The high density of archeological sites (1 site/10 acres) has made facility expansion and modernization difficult. Three cultural resource management challenges are discussed below with opportunities highlighted for the application of the 3-dimensional predictive model of CHILD.

Facility Modernization

Much of LANL was built during the early Cold War period (1947-1963). Today the physical plant of the Laboratory is antiquated and plans are being developed to modernize. However, the risks involved in inadvertent discovery of buried archeological material and prehistoric inhumations have contributed to limiting modernization at the Laboratory to areas that have previously been developed. The environmental costs associated with building new facilities in undeveloped areas are high. The ability to predict the location of buried archeological remains across the landscape would greatly facilitate the planning process for Laboratory modernization. The archeological application of the CHILD model could become an important planning tool at the Laboratory.

The Cerro Grande Fire Recovery

The recent Cerro Grande fire (May 5-July 30, 2000) has highlighted another important application of the CHILD model for Los Alamos National Laboratory. In the late morning of May 5, 2000, a prescribed burn at Cerro Grande, located in the Northwest corner of Bandelier National Monument burned through the control line and spread to the Santa Fe National Forest located to the west and directly up-slope from the Laboratory (Figure 4.2). By the late afternoon of May 5, the Cerro Grande fire was buring out of control and rapidly moving north, driven by high winds. On May 8, 2000 the town of Los Alamos was evacuated and the fire spread to the town site (Fire Investigation Team 2000). On May 10, President Clinton declared Los Alamos a disaster area. The Cerro Grande fire ultimately burned 43,000 acres, destroyed 400 homes and burned 25% of Los Alamos National Laboratory. It represents the worst forest fire in New Mexico history with projected costs of the fire exceeding 1 billion dollars.

The fire severely burned the mountain slopes above the Laboratory placing the down slope facilities at high risk for catastrophic floods for the next 3-5 years. As vegetation re-establishes itself, the risk of flooding will decrease. It is estimated that the hydrophobic soils resulting from the high intensity fire on the hill slopes will result in a 100 year, 6 hour flood event being 10 to 100 times more severe than normal. At these projected rates, massive debris flows will threaten not only cultural resources, but facilities as well. The erosion and movement of potential release sites is also a major risk. The flood estimates have been used to plan flood control measures (weirs, dams, hay wattles, water retention structures, etc.) in the hill slopes and canyon bottoms across the Laboratory. However for the lack of a simulation environment, the long-term landscape changes due to the fire have not been modeled. It is clear that these effects will significantly alter the present landscape but where and to what extent these changes will take place remains difficult to predict. The long-term effects of flood controls are also hard to predict and over time could have unintended consequences for cultural resources down stream. The CHILD model, with its integrated hill-slope and channel approach, is designed to address these uncertainties and could provide the modeling and simulation environment to explore the long-term effects of different alternatives to flood control.

The Cerro Grande fire also provides an opportunity to test the CHILD model over the course of the fire recovery period (3-5 years). The Laboratory intends to acquire remote sensed data biannually to track fire effects over time. This is an excellent opportunity to test the ability of CHILD to accurately model landscape changes and predict the effects on archeological sites. Information from this study can be used to improve the model's predictive capabilities.

Routine Operations and Maintenance

The Cultural Resources Team at Los Alamos National Laboratory reviews between 800 and 1100 projects a year for potential effects to cultural resources. The majority of these projects involve some degree of excavation. At present there is no systematic, probabilistic method available for predicting the location of buried archeological sites. In the past, inadvertent discoveries of prehistoric burials have caused

delays and resulted in unanticipated costs to projects. The application of the 3-dimensional predictive modeling capabilities of CHILD to this problem would enhance project planning and project review.

Data Sources

The Laboratory is involved in an enhanced data acquisition process due to environmental restoration requirements on Laboratory lands resulting from mission related activities. New data sources are discussed below:

1) Digital Elevation Model (DEM): The most important data source for running the CHILD model is an accurate, high resolution DEM. The Laboratory has a light detection and ranging (LIDAR) instrument DEM that was acquired in June, 2000. This DEM is accurate to $\pm$ 15 cm at 1 foot resolution. This DEM will be an invaluable resource for running simulations.
2) Multi-spectral remote sensing data: The Laboratory will acquire 4 m Airborne Visible/Infrared Spectrometer (AVIRIS) data in September. It is hoped that this data will be able to characterize changes in sedimentation. The Jet Propulsion Laboratory will collect ground spectra during the flyover and archeological sites will be included for later calibration and classification of the data .
3) GIS data: The Cultural Resources Team at the Laboratory has maintained a GIS data base of archeological sites by period of occupation. Many of these sites are located at the sub-meter, differential GPS, accuracy. Other primary data layers include vegetation, hydrology, facilities and roads, and geology.
4) Soils Map: The Laboratory has developed the soils map for Los Alamos County and it is a data layer in the LANL corporate GIS database.
5) Hydrology: The Environmental Safety and Health Division (ESH-18) has developed a Groundwater Protection Management Plan that contains much useful data for running the CHILD simulation such as data from surface water gauging stations, stratigraphy and sediment characterization across the Laboratory.
6) LANL geomorphologist, Steve Reneau, has developed landform age data for much of the facility that will be important in calibrating the CHILD model.
7) Computer resources: Los Alamos National Laboratory has "state of the art" computing capabilities.

Feasibility of Technology Demonstration

It is clear that the cultural resources management issues, although different from those that exist on Army training installations, would benefit from the application of the CHILD model. The benefit to the facility planning and project review process are significant. Data sources at the Laboratory are capable of supporting the CHILD simulations and computer capabilities at the Laboratory are "state of the art". It is also important to emphasize that if the technology demonstration is successful, technology transfer of the CHILD model to other DOE facilities would be possible. Therefore, a demonstration at Los Alamos National Laboratory is a logical "next step" in the development of the CHILD application.

CHAPTER 5
Conclusions

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The combined research efforts advocated in our original SERDP proposal and presented in detail herein address an important concern of military land managers; that is, *where on the landscape are the resources located and where are they at risk?* In this case, we are dealing with surface and subsurface archaeological resources and to fully comprehend the problem and mitigate the risk, we must adopt a three-dimensional approach to the landscape and the formation of the archaeological record within that evolving landscape. We argue that there is a very significant "value-added" component in this approach when compared to the traditional 2-D approach to predictive modeling and archaeological inventory survey. Surface archaeological distributions represent only a fraction of the total archaeological record. Subsurface sites represent a sizable portion of that record and are not necessarily protected from adverse military-unique impacts just because they happen to be buried. We need to determine the nature of archaeological sensitivity across the installation landscape and then assess the potential threat to these resources from subsurface military training/testing/construction impacts. In other words, we need to assess how deep these resources are over the landscape, as well as how deep the military impacts might be and where they might coincide with both the surface and subsurface archaeological record.

This 3-D approach to landscape evolution and predictive archaeological modeling advocated here will provide a cost-effective method for potentially identifying both surface and subsurface archaeological sites that represent a potential risk to Army, DoD, and DoE training and testing activities. It provides a *proactive* means of predicting (and thereby avoiding) inadvertent discoveries of archaeological resources and Native American human remains and traditional cultural properties. It also promotes the use of more efficient and cost-effective methods of site detection in archaeological inventory surveys by linking those methods and protocols to particular landforms and geomorphological contexts. As a long-term consequence, it will enhance DoD/DoE stewardship responsibilities for the archaeological resources under their jurisdiction as well as protect the military training mission from unanticipated delays.

Finally, it should be noted that the CHILD model could benefit military land managers in a more direct fashion by simulating short- and long-term landscape responses to military training impacts. The results of such simulations would be of broad interest to all resource managers and could provide insights into scientific "best practices" for the long-term sustainability of the training landscape as well as the long-term stewardship of its natural and cultural resources.

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FIGURES

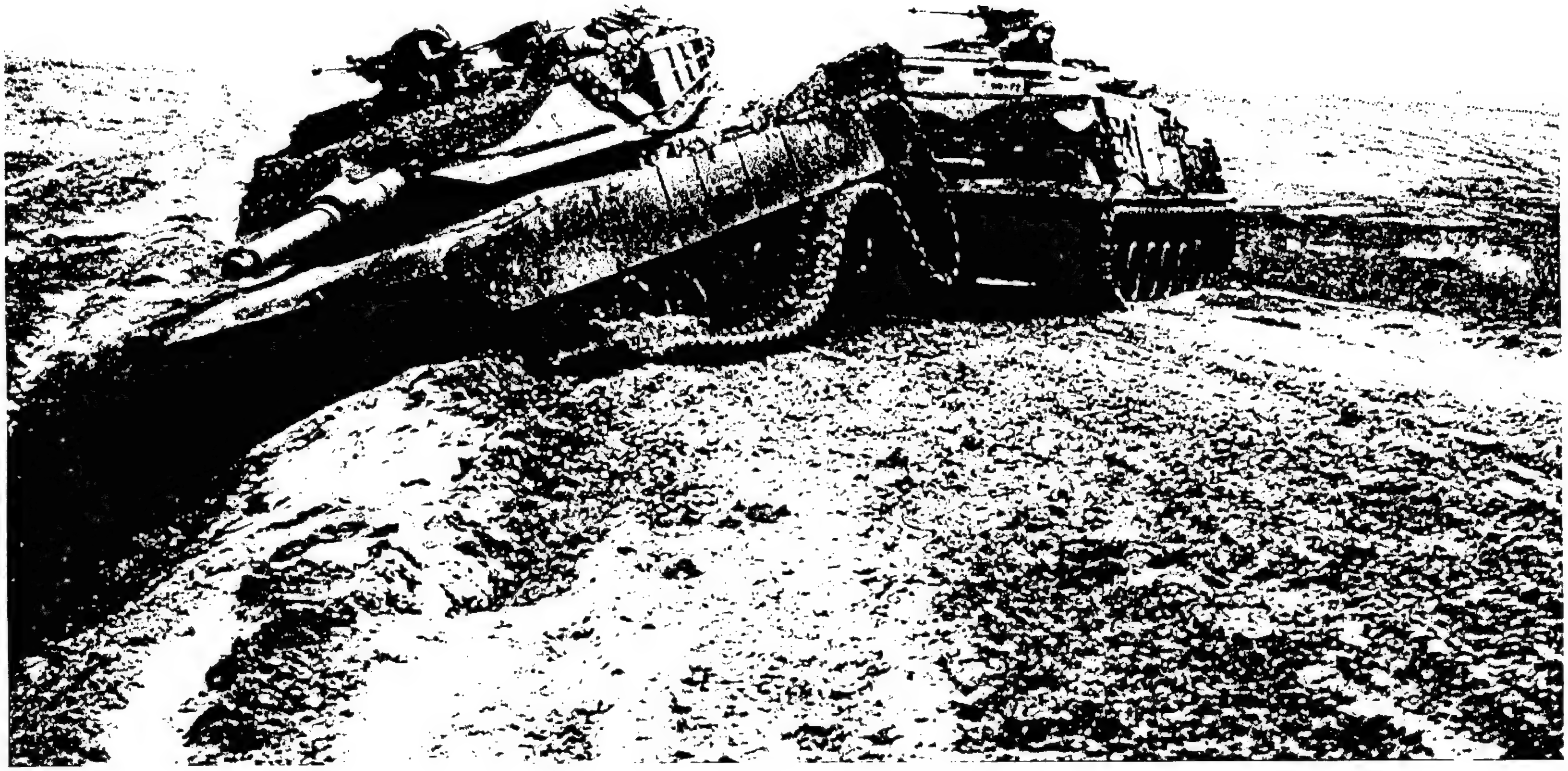


Figure 1.1. Mechanized training exercise showing severe soil disturbance and high potential for erosion.

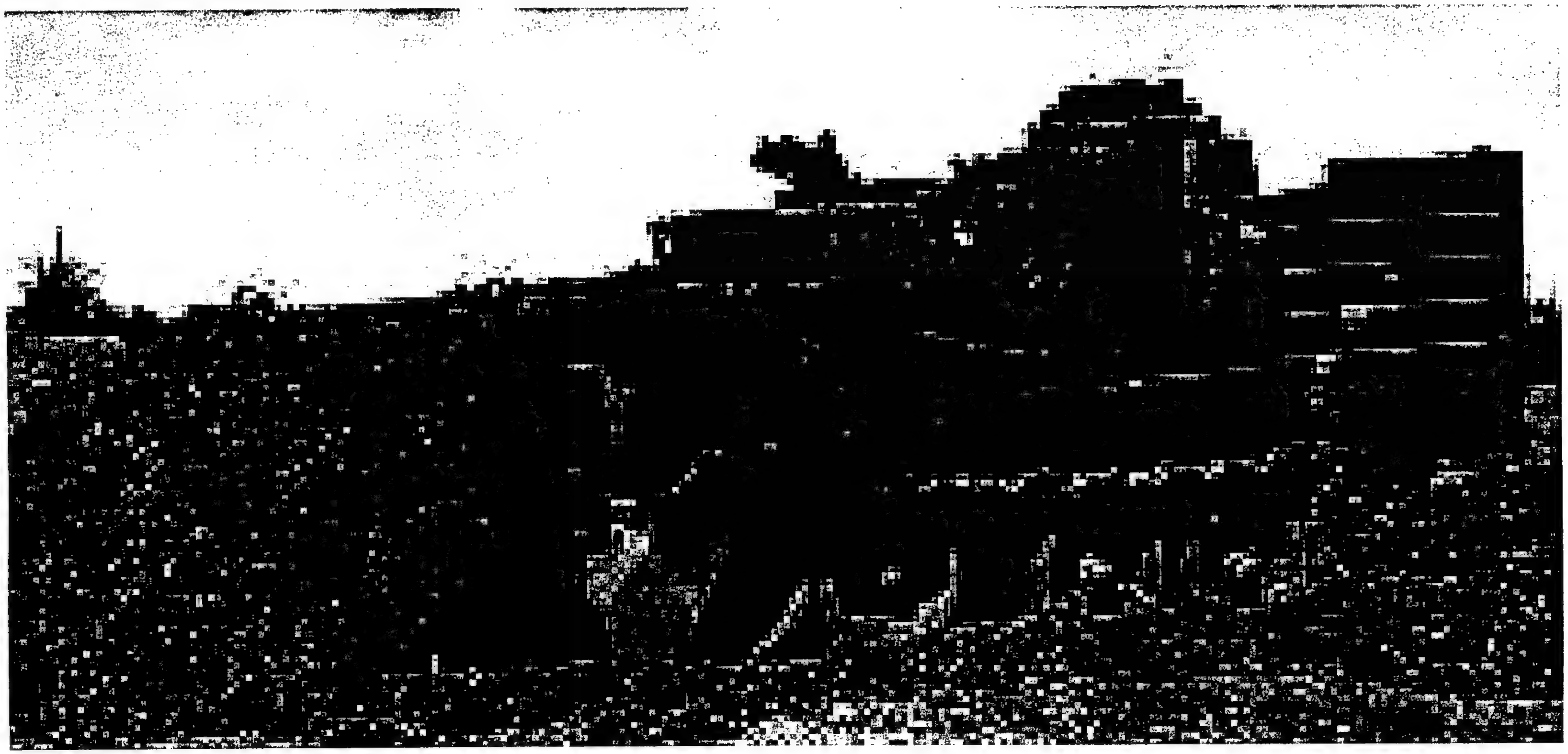


Figure 1.2. M9 ACE engaged in mechanized digging activity for combat training.

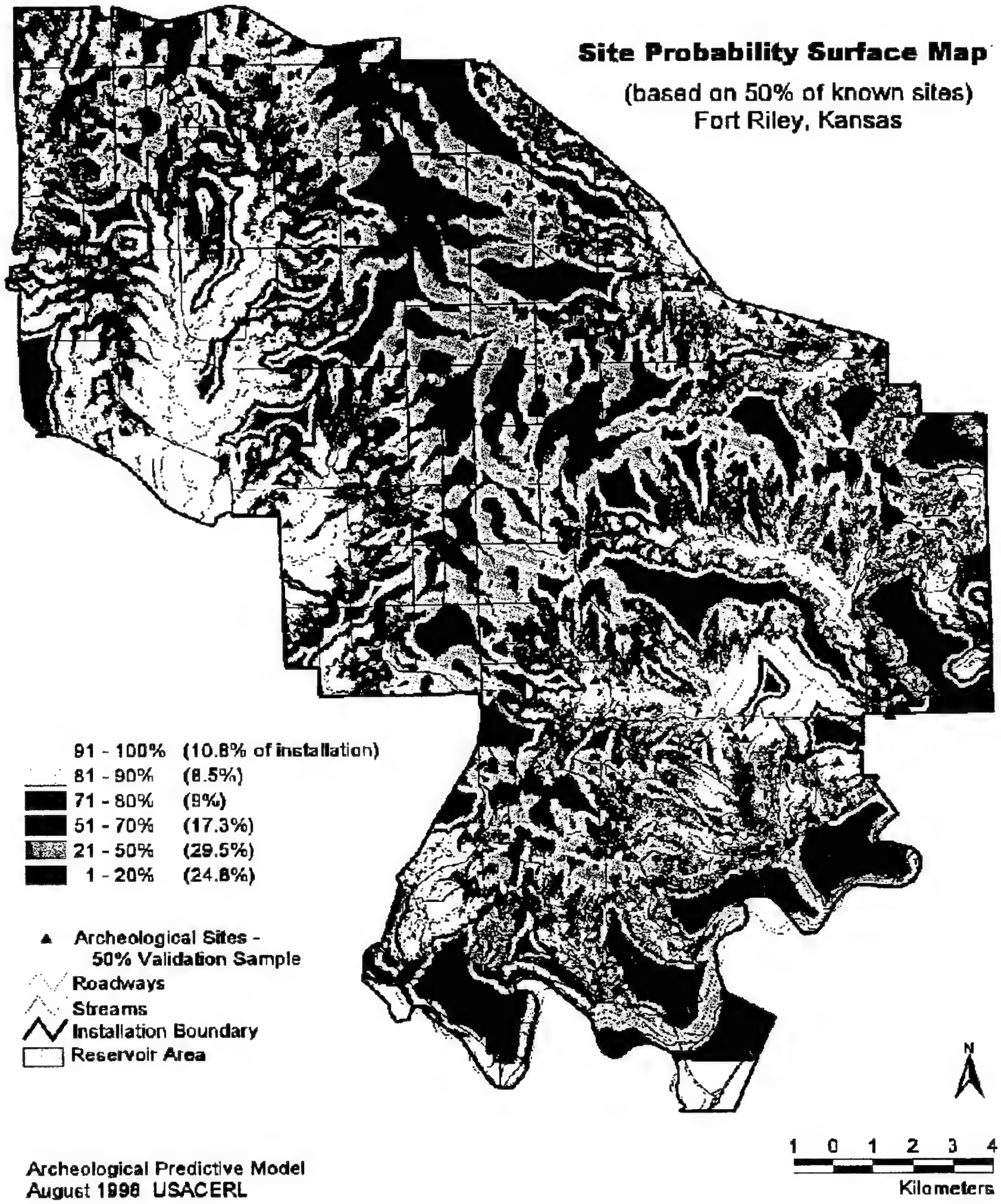


Figure 1.3. Two-dimensional predictive archaeological model for Fort Riley, Kansas

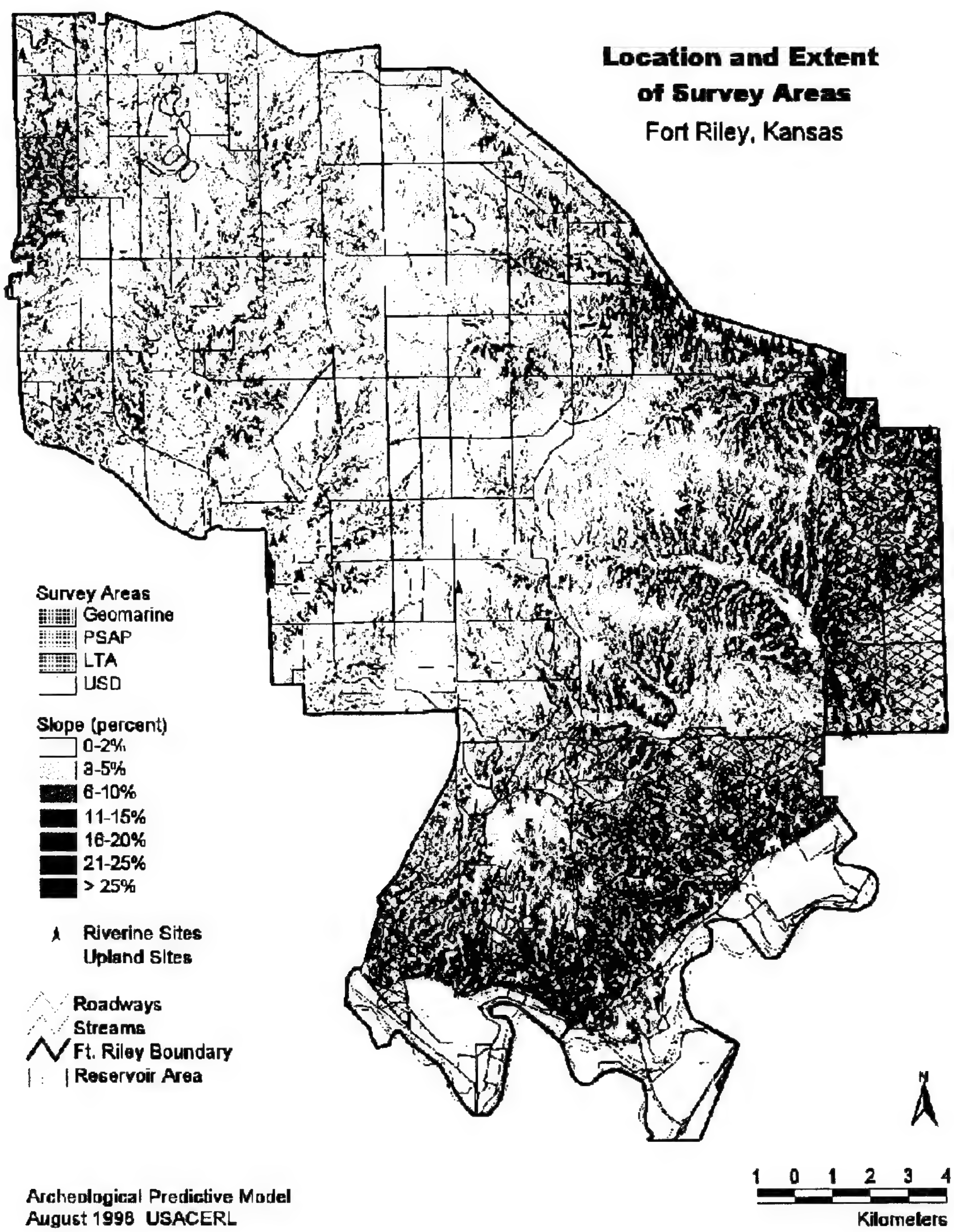


Figure 1.4. Archaeological survey areas and surface site distribution at Fort Riley, Kansas.

Pump House Canyon Pit

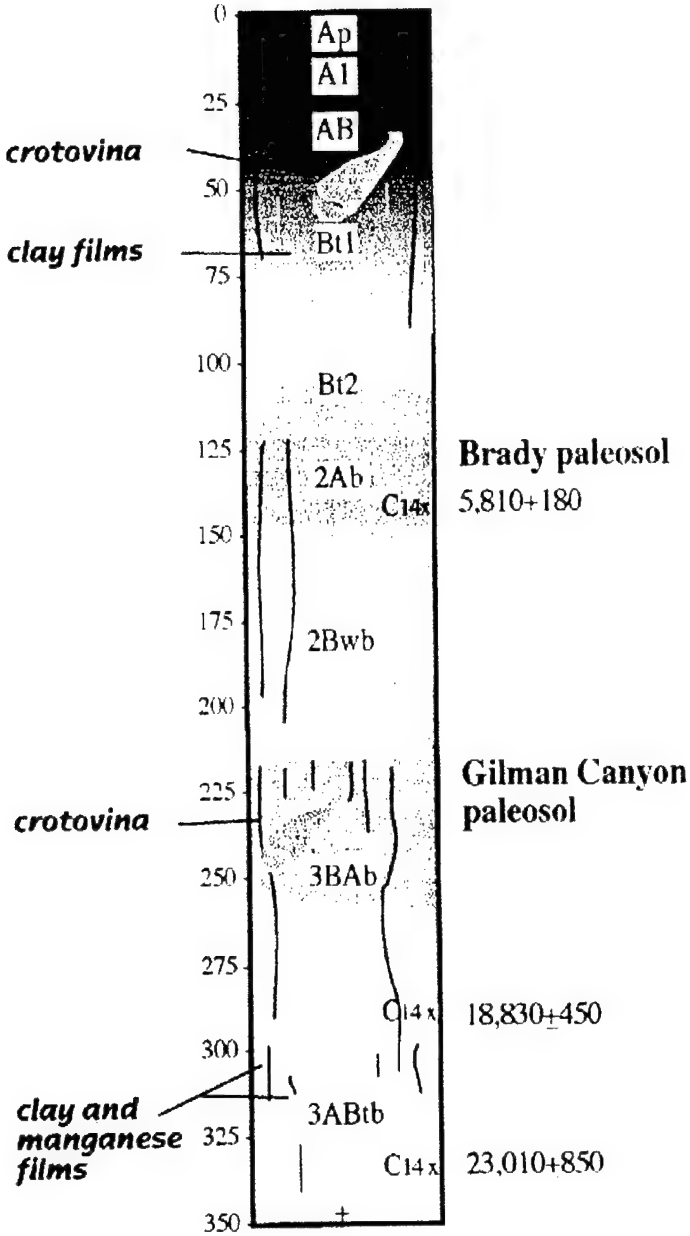


Figure 1.5. Deep geomorphic sediment column in upland zone at Fort Riley, Kansas, showing buried mid-Holocene cultural horizon associated with the Brady paleosol.

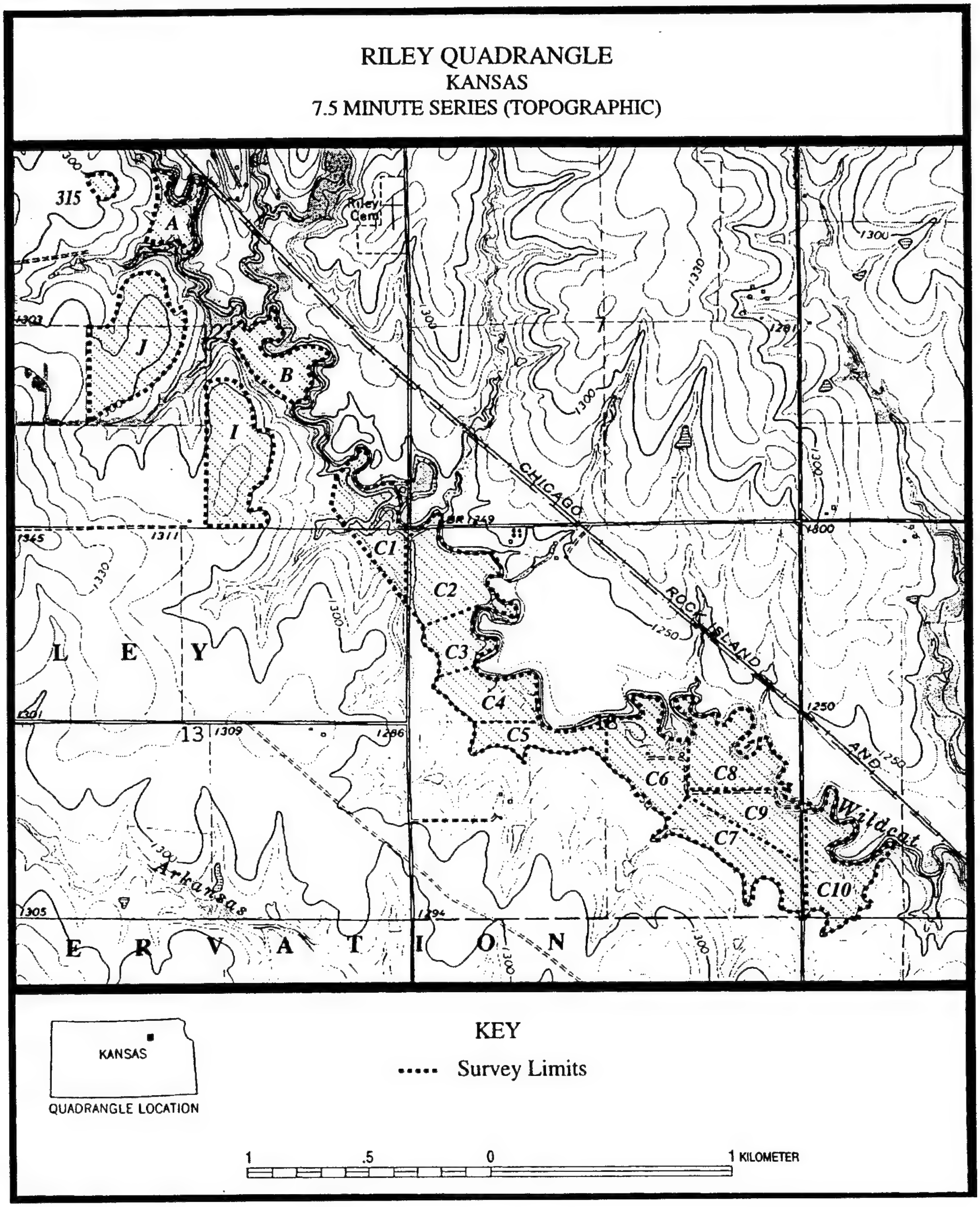


Figure 1.6. Archaeological survey tracts along the right bank of Upper Wildcat Creek drainage, Fort Riley, Kansas, where traditional survey methods were employed to locate surface manifestations of archaeological sites. (Source: Kreisa and Adams 1998).

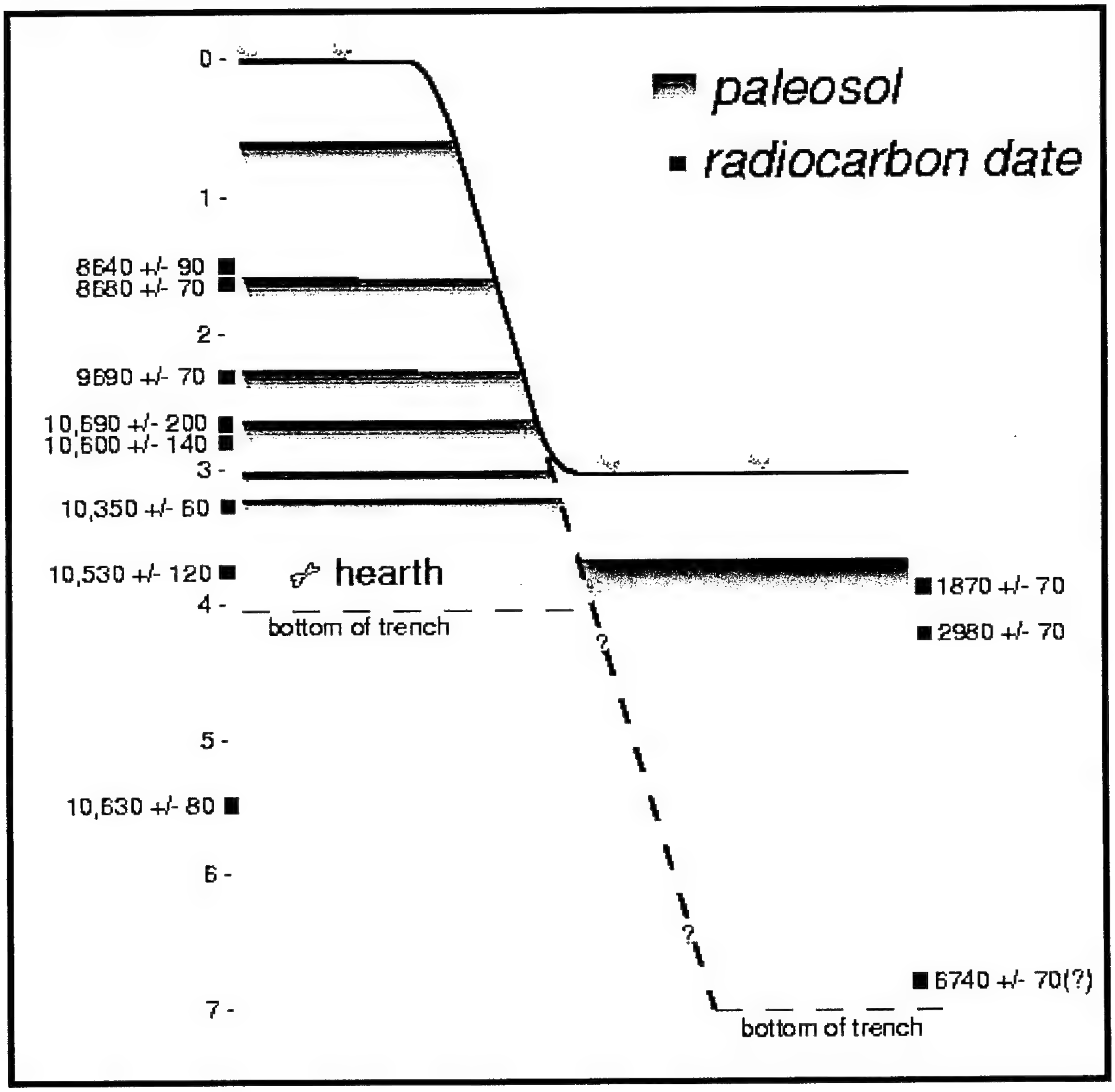


Figure 2.1. Schematic cross-section of two stream terraces from Forsyth Creek, Fort Riley, Kansas. Both terraces show dates paleosols. A buried hearth is found at 4-m deep in the higher and older terrace. (Source: Johnson 1998).

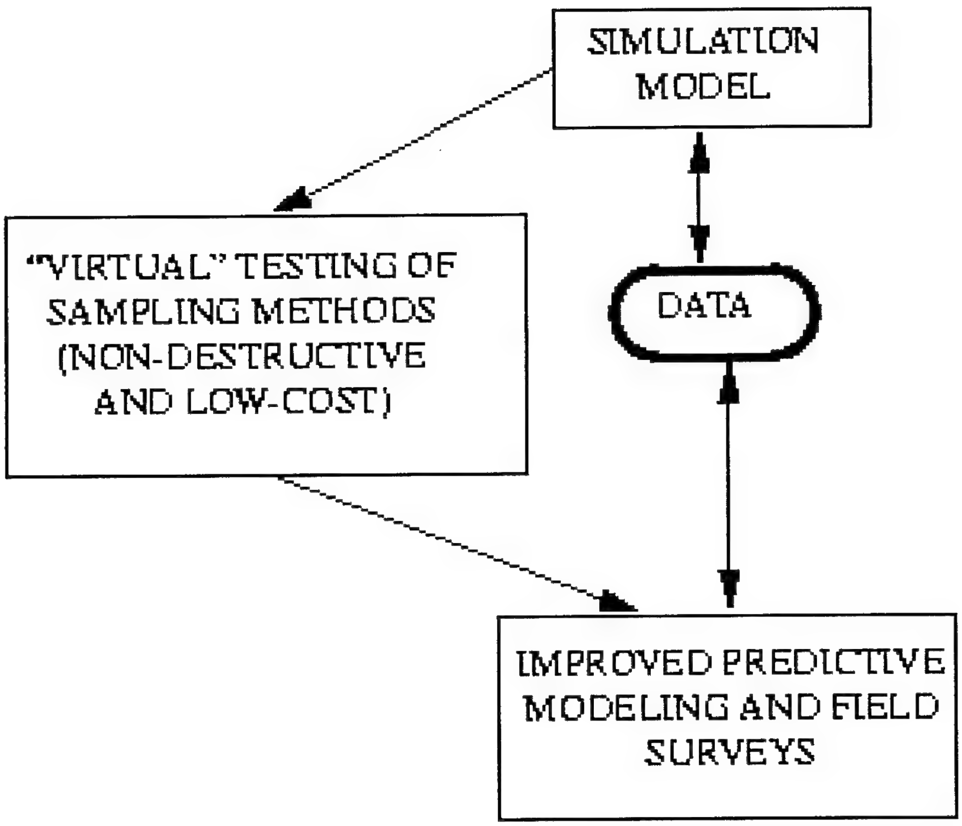


Figure 2.2. Flowchart illustrating the approach followed in this study.

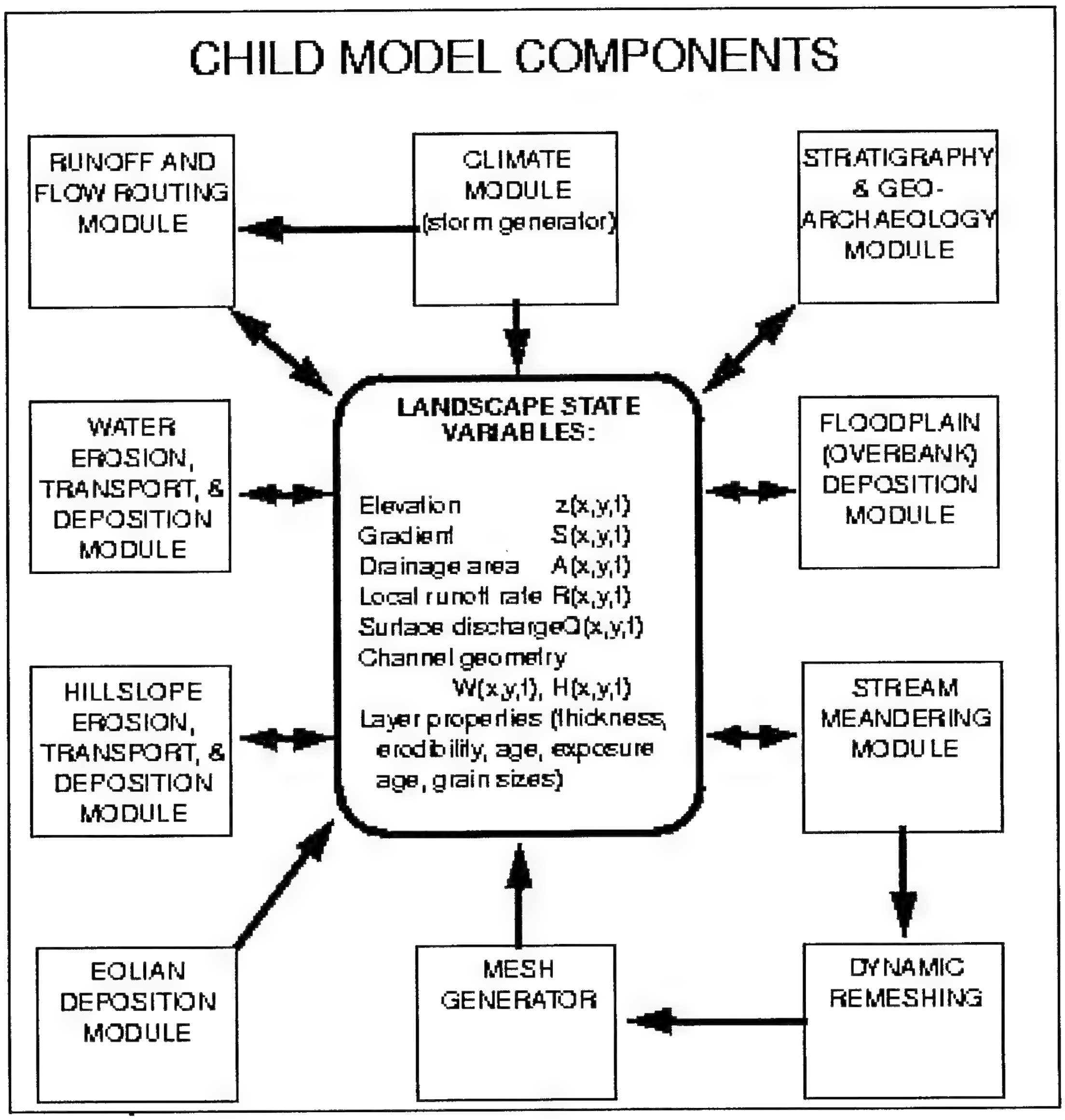


Figure 2.3. Schematic illustration of the state variables and process modules in the CHILD landscape evolution model.

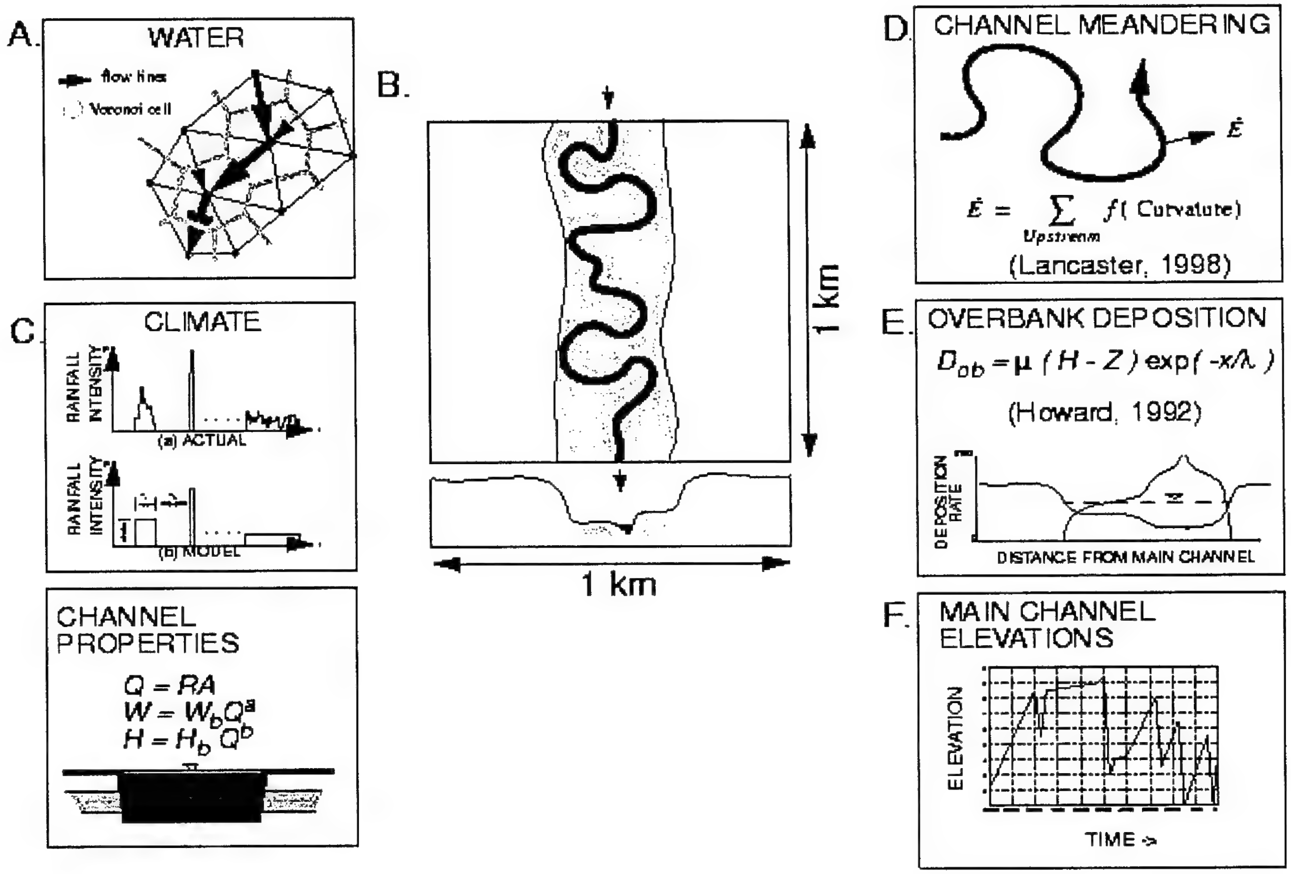


Figure 2.4. Process and boundary conditions in the Wildcat Creek simulation with the CHILD model. A. Flow-routing (blue) from point to point in the steepest downward slope in a TIN framework (black) and corresponding voronoi cell (gray). B. Boundary conditions and initial spatial domain (light green); the main stream is fed in at the head of the valley and exits out at the bottom. C. Climate is modeled as a succession of storm and interstorm periods, each with a constant rainfall intensity. D. The channel is treated as a one-dimensional object and its meandering is simulated using the model of Lancaster (1998). E. Overbank deposition is modeled with a diffusion equation, in which sedimentation rate depends on flood height relative to surface height and distance from channel. F: The main channel elevation is constrained by the floodplain history recorded at Pomme de Terre River (Missouri) by Brackenridge (1980).

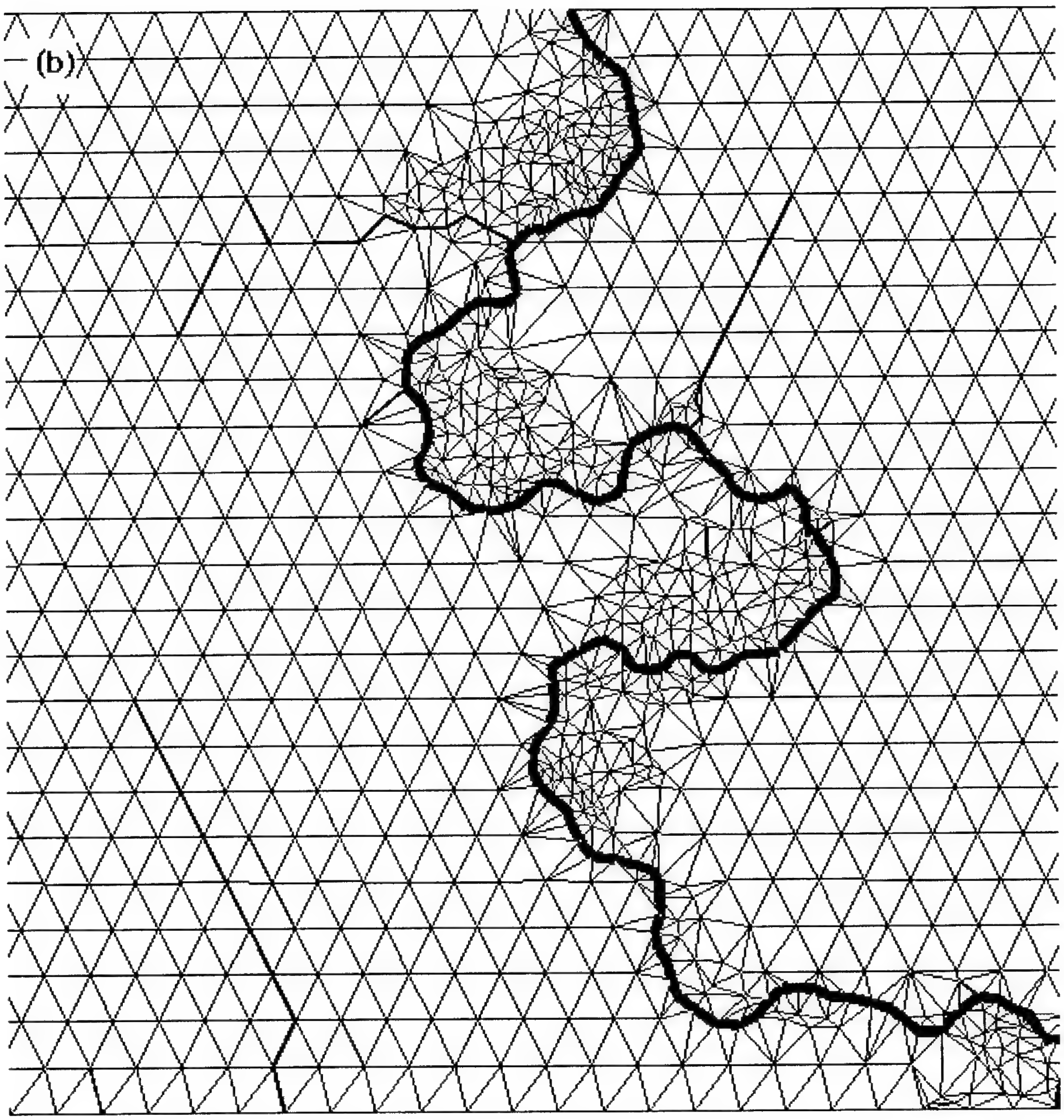


Figure 2.5. Adaptive simulation mesh, highlighting the use of dynamic remeshing to model lateral channel movement.

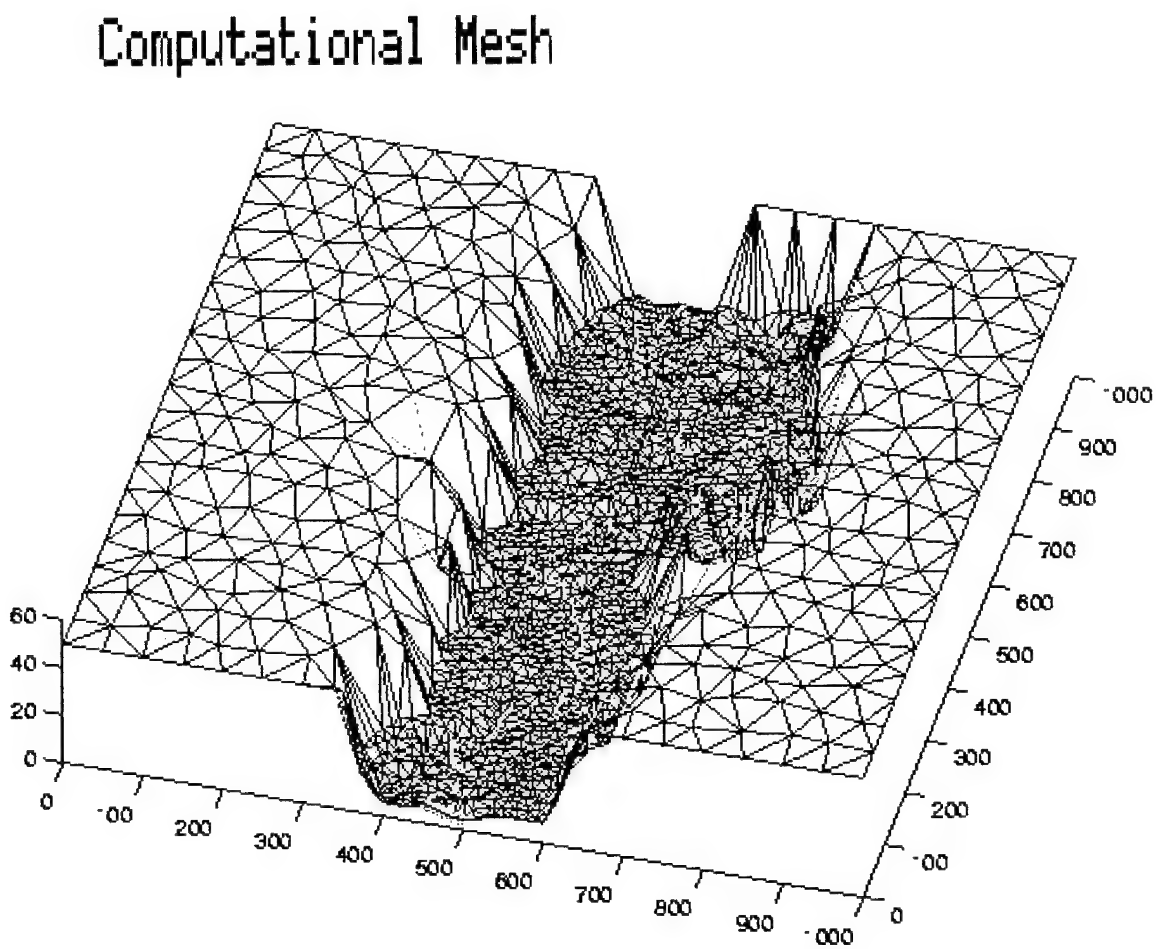


Figure 2.6. Perspective view of the Wildcat Creek computational mesh showing the refinement of the mesh in the valley and the channel in blue.

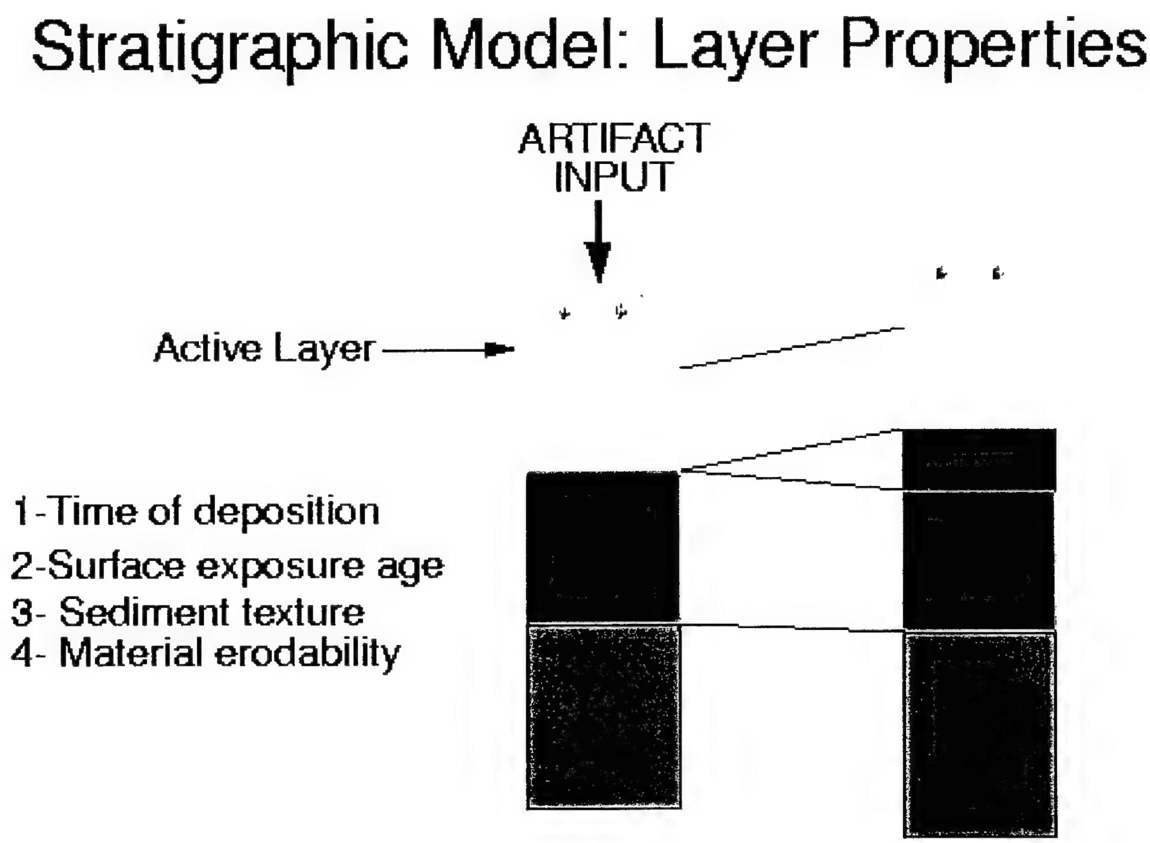


Figure 2.7 At each node of the mesh, the stratigraphy is recorded as a column of layers with variable thickness and properties such as the time of deposition and surface exposure age.

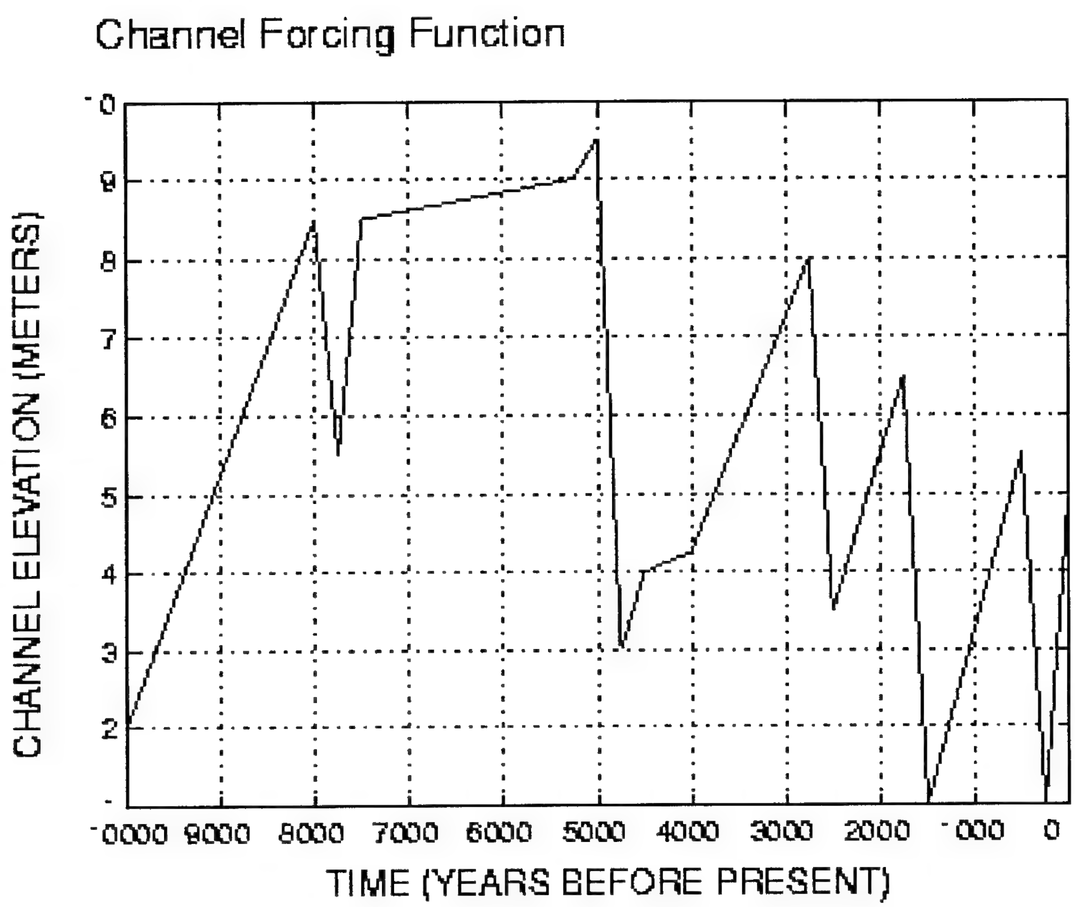


Figure 2.8. Channel forcing function. Channel elevation of the Pomme de Terre River (Missouri) reconstructed with radiocarbon terrace dates by Brackenridge (1980).

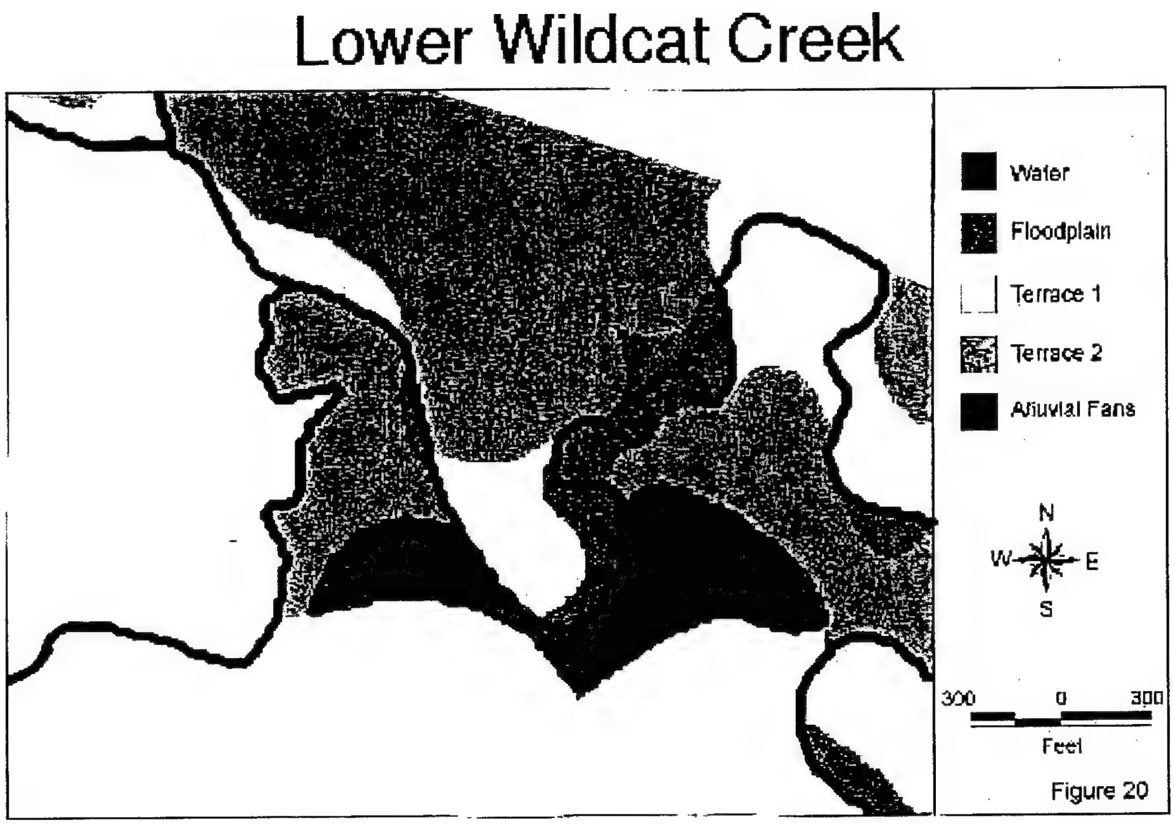


Figure 2.9. Lower Wildcat Creek alluvial plain map showing Quaternary formations: Terrace 2 is older and higher (orange); Terrace 1 is lower and more recen (yellow); current deposits are shown as floodplain (purple).

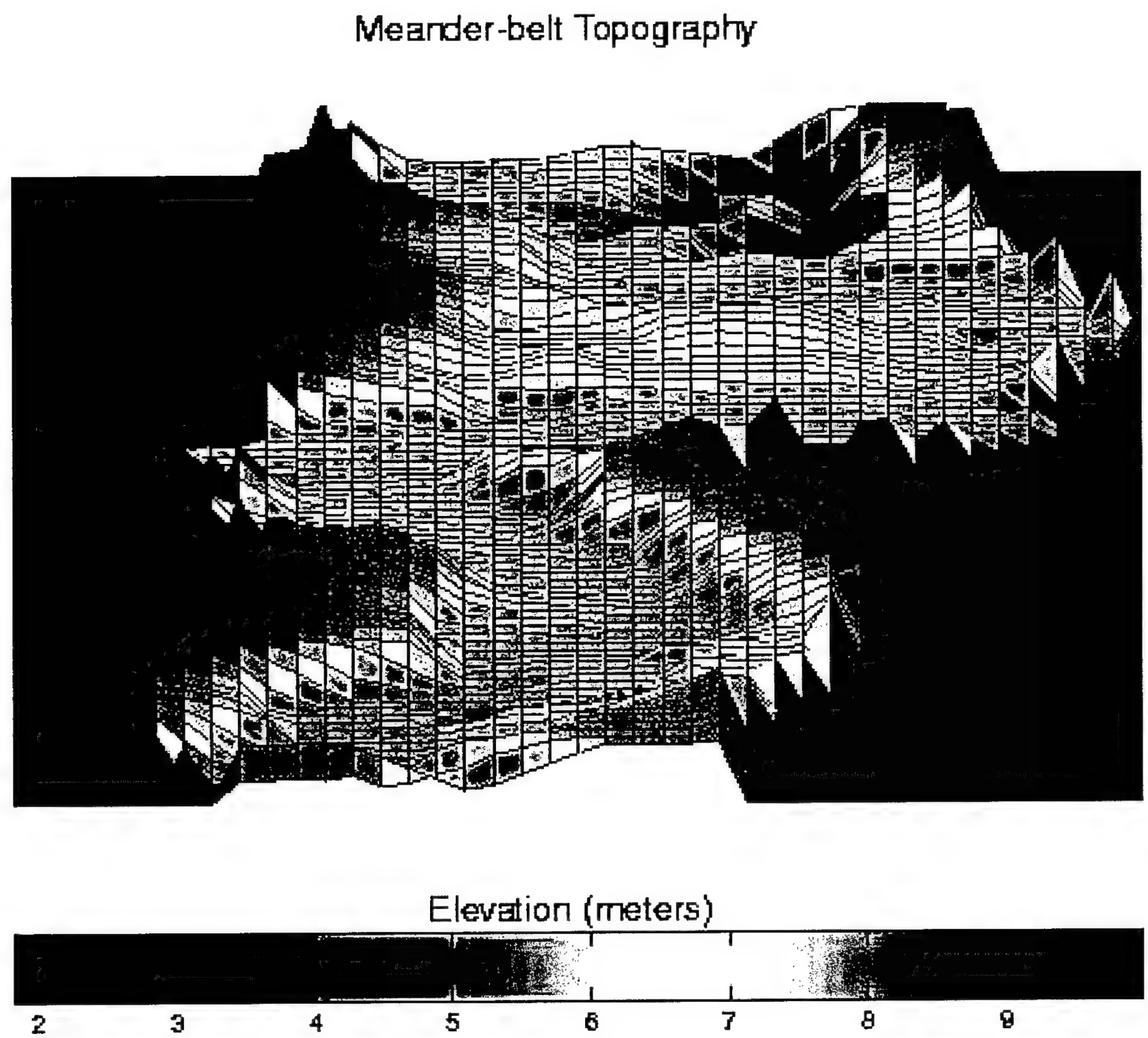


Figure 2.10. Perspective view of topography of the modeled meander belt.

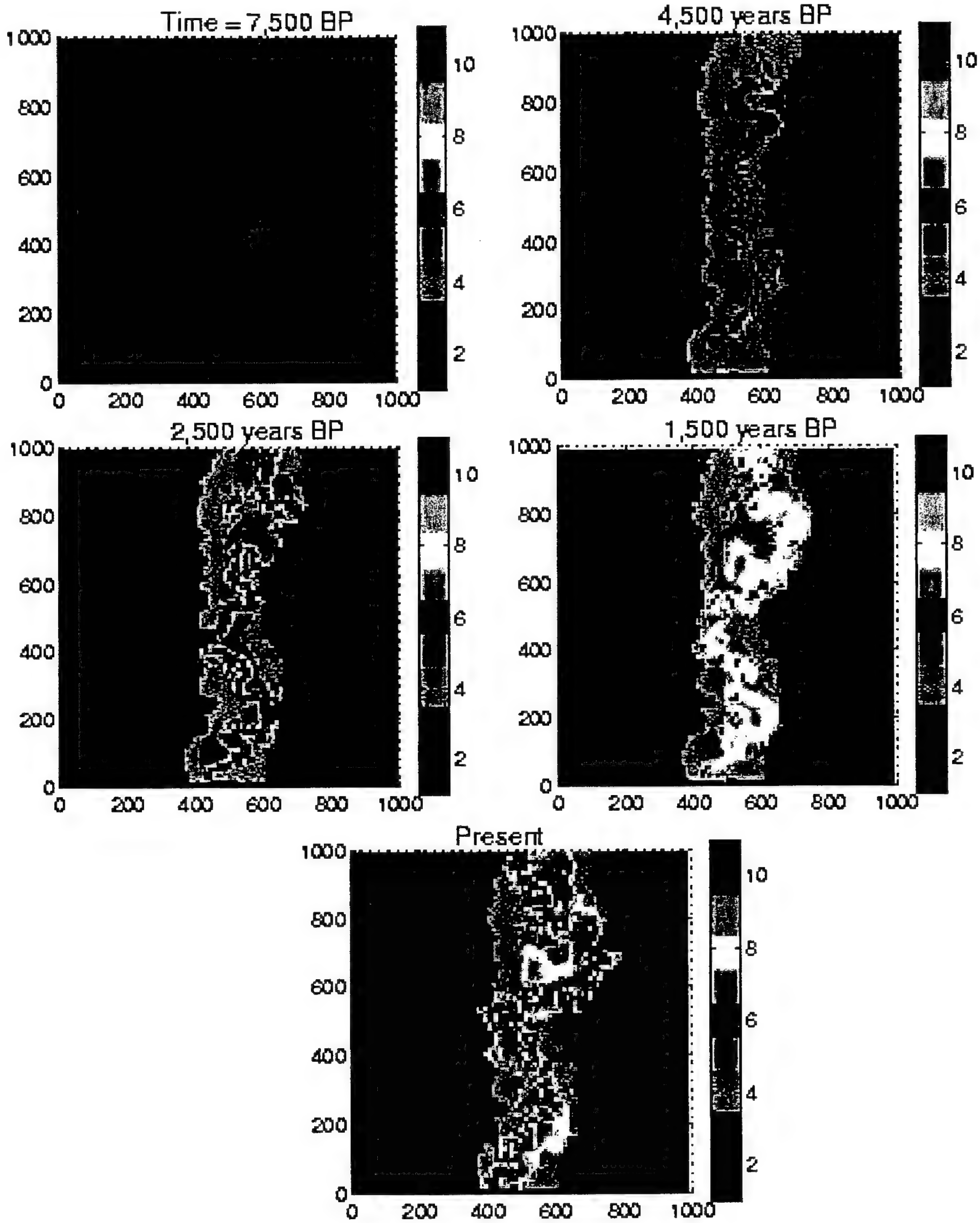


Figure 2.11. Time-series of the age (time of deposition) of surface material. Material age is grouped by periods of rise and fall of the stream (see channel forcing function curve, Figure 8). For example, age "1" corresponds to any material deposited during the rising period of the channel from 10,000 years BP to 8,000 years BP.

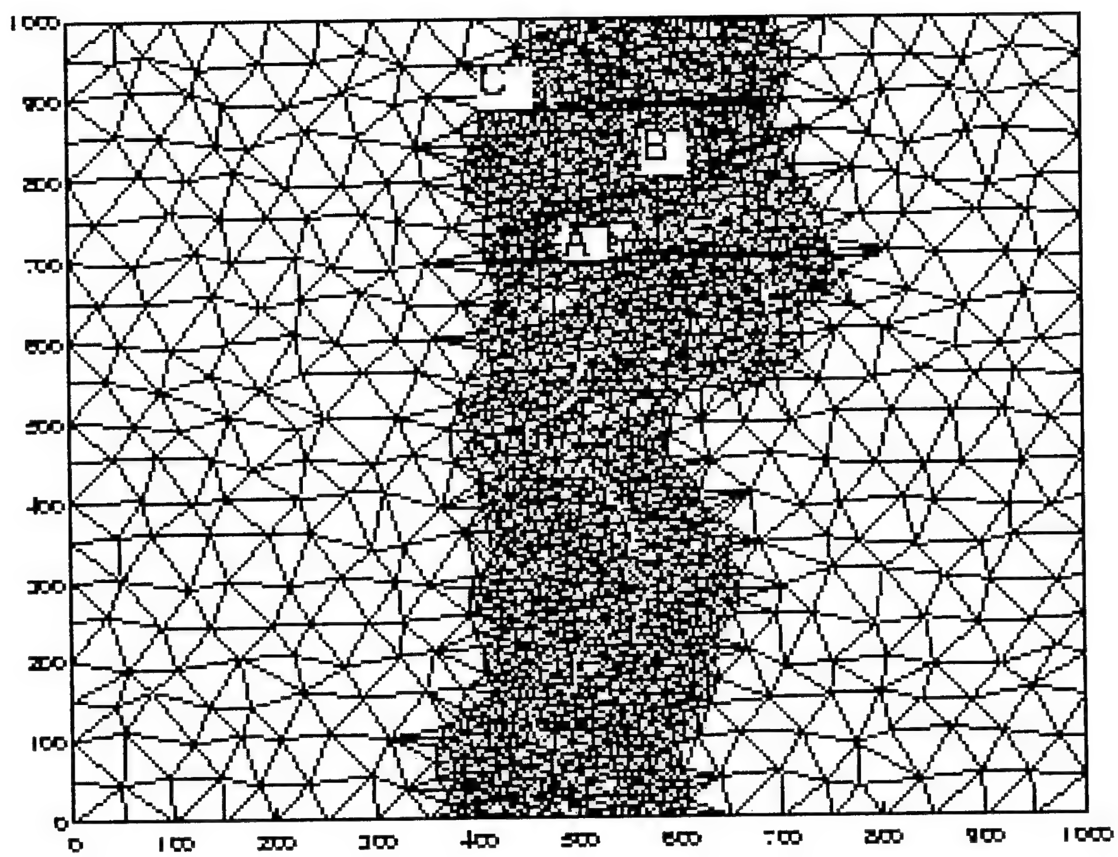


Figure 2.12. Plan view of mesh showing the location of the three stratigraphic cross-sections (A, B, and C).

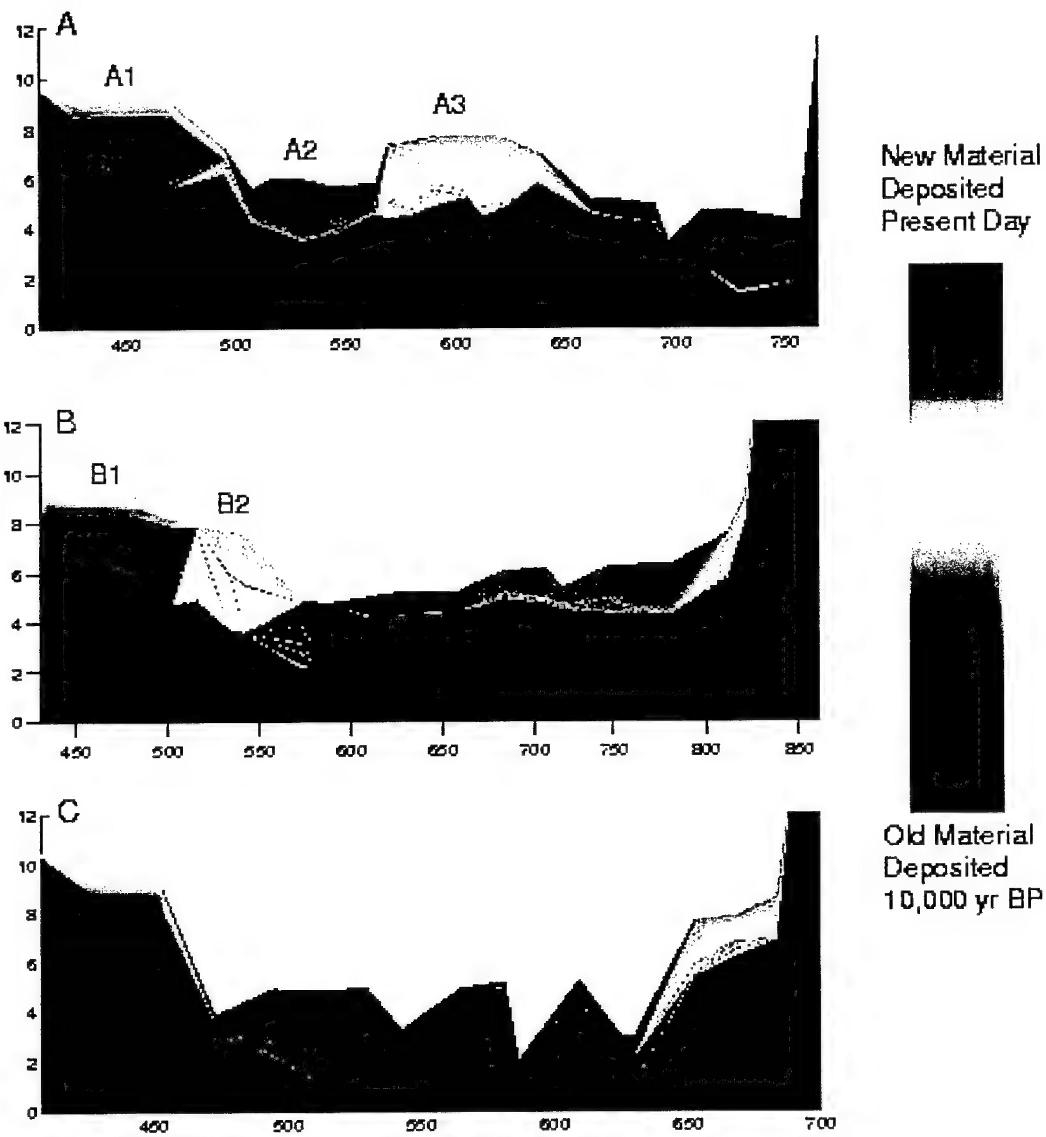


Figure 2.13. Cross-sections illustrating alluvial stratigraphy, shaded by the time of deposition of materal.

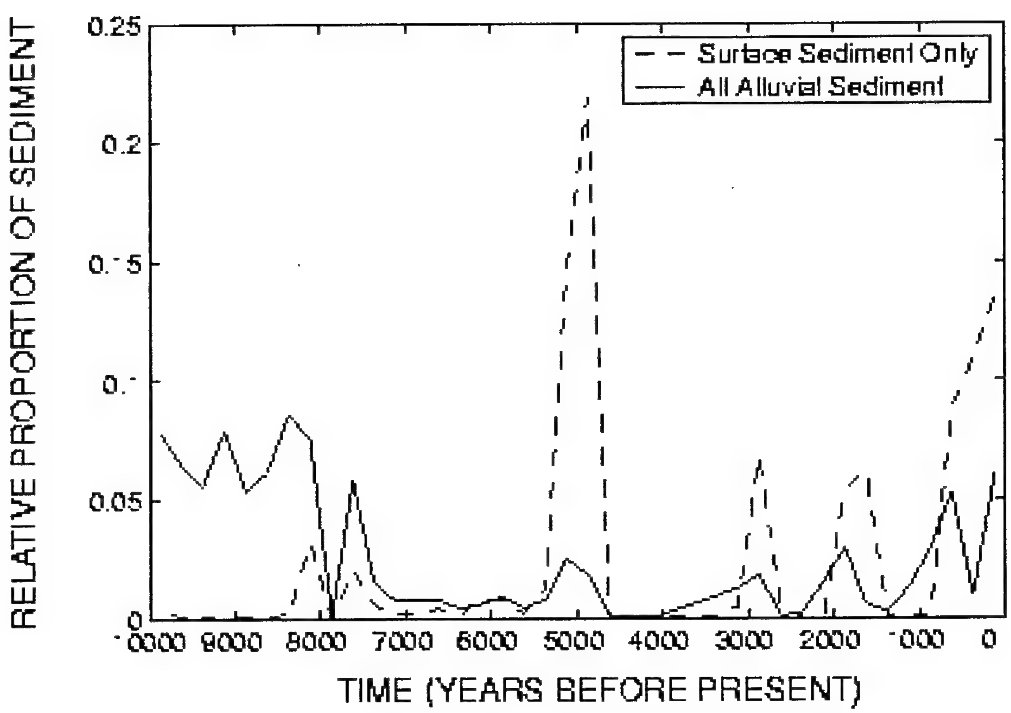
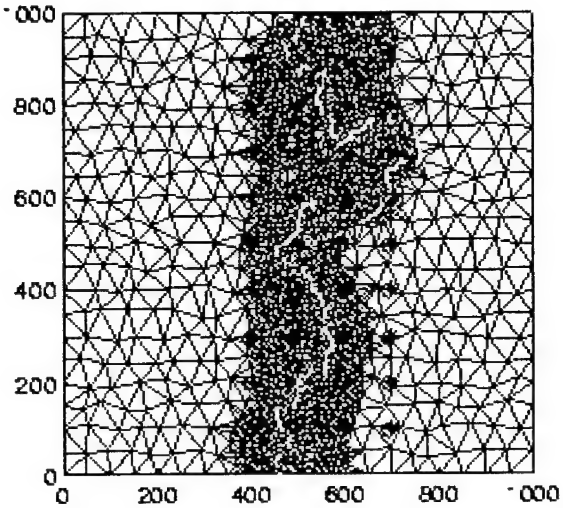
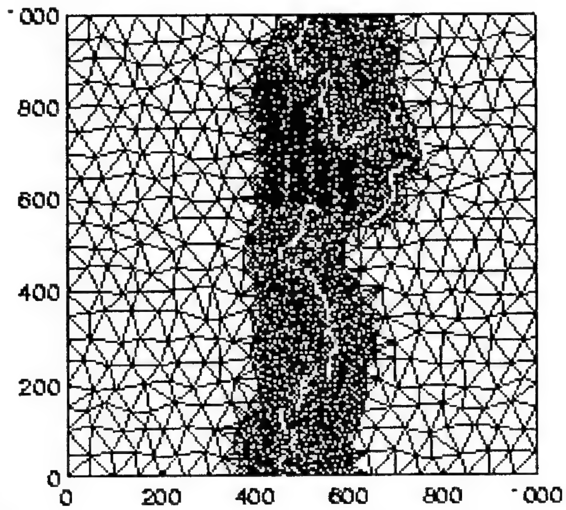


Figure 2.14. Age distribution of the alluvial sediments at the surface and in the "all alluvial sediment" formation.

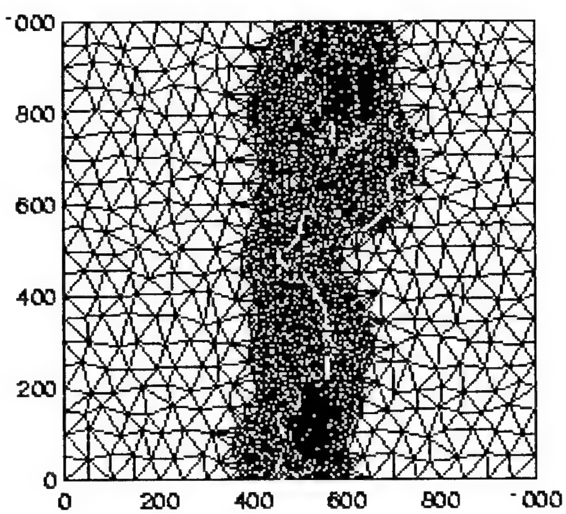
Scheme 1 - 36 pits (black circles), each of unit area and 0.5 meter depth. Spacing is regular with no regard for terrace age.



Scheme 2 - 36 pits (black circles), each of unit area and 0.5 meter depth. Spacing is fairly regular, but samples are only taken from two old terraces.



Scheme 3 - 36 pits (black circles), each of unit area and 0.5 meter depth. Only sampling on terraces, but this time only younger terraces are sampled.



Scheme 4 - 18 pits (black circles), each of unit area and 1.0 meter depth. Regular spacing, only sampling on one of the oldest terraces, but investigating deeper pits.

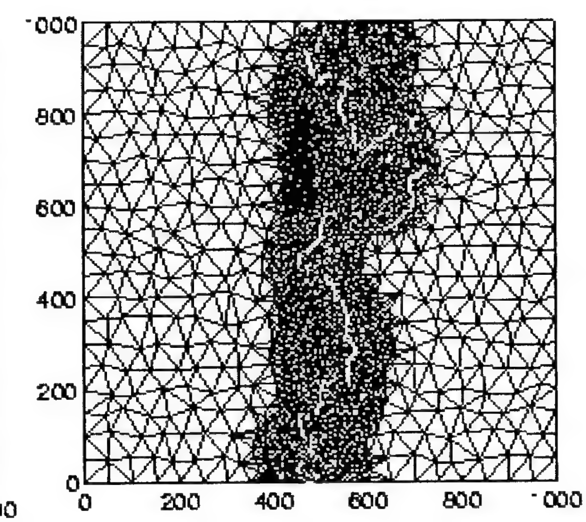


Figure 2.15. Grids used for Monte Carlo simulation of artifact deposition.

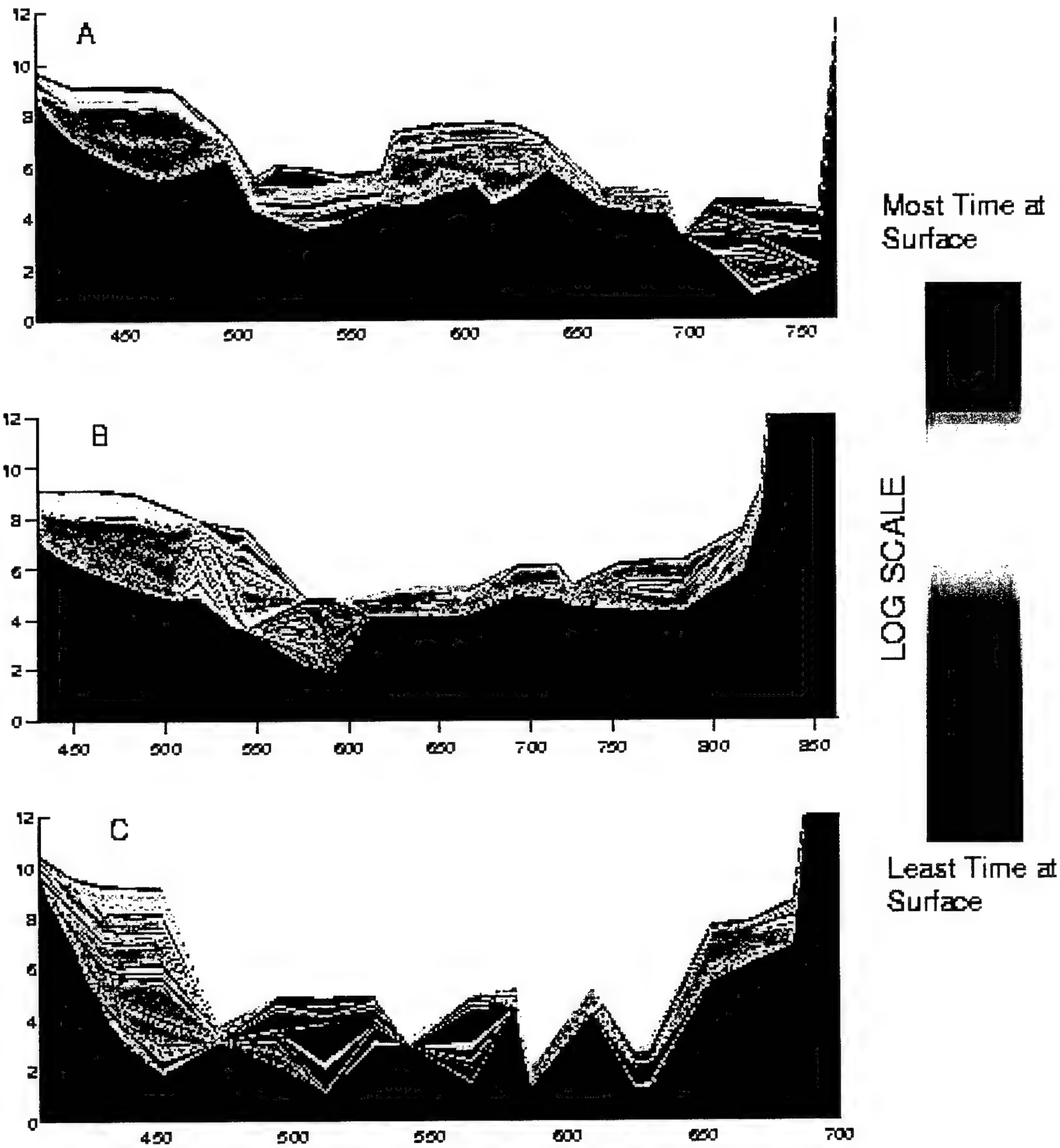


Figure 2.16. Cross-sections illustrating alluvial stratigraphy, shaded by amount of time material spent at surface (surface exposure age).

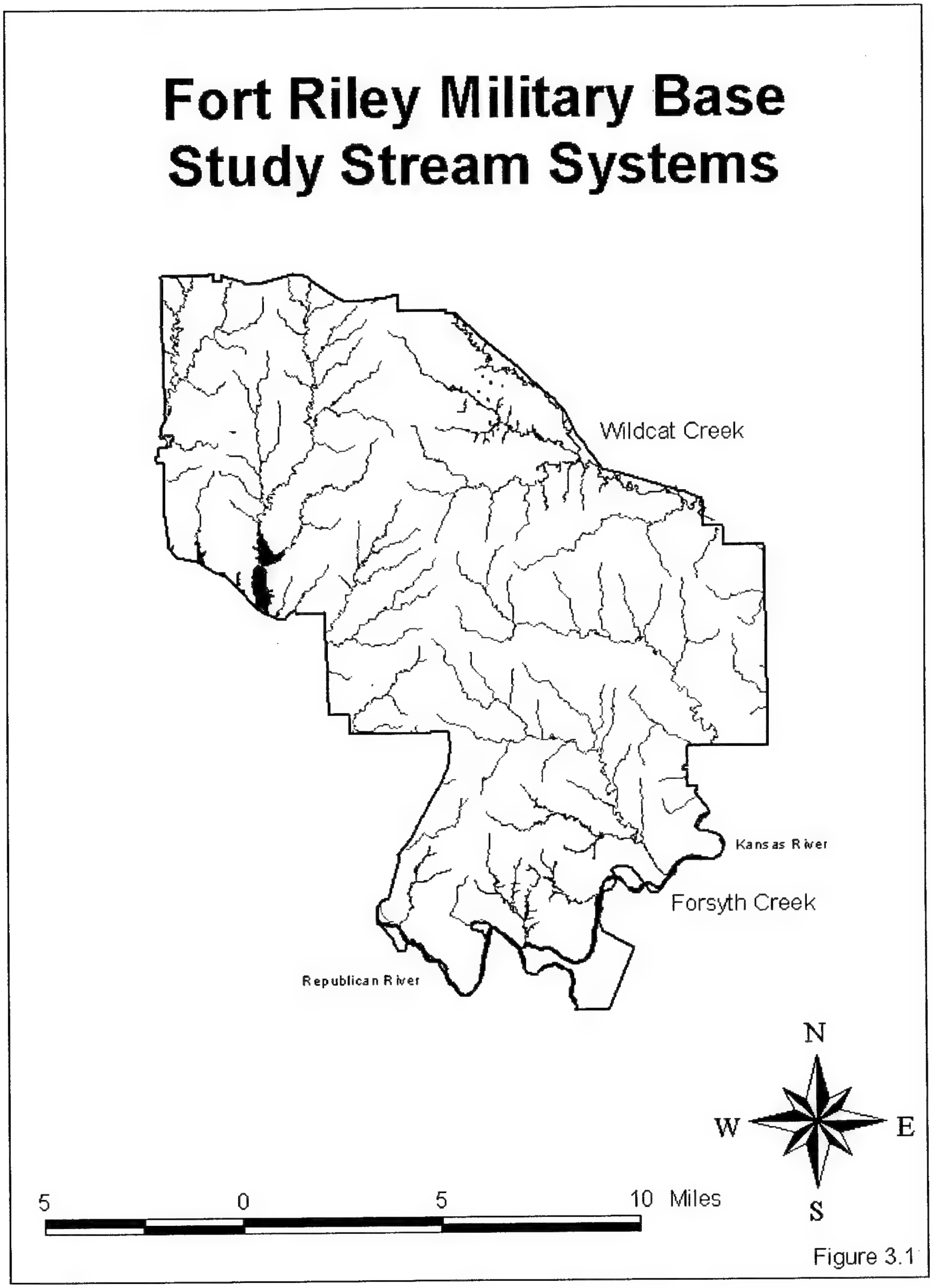


Figure 3.1. Hydrologic map of Fort Riley, Kansas, showing drainages discussed in the text.

Forsyth Creek

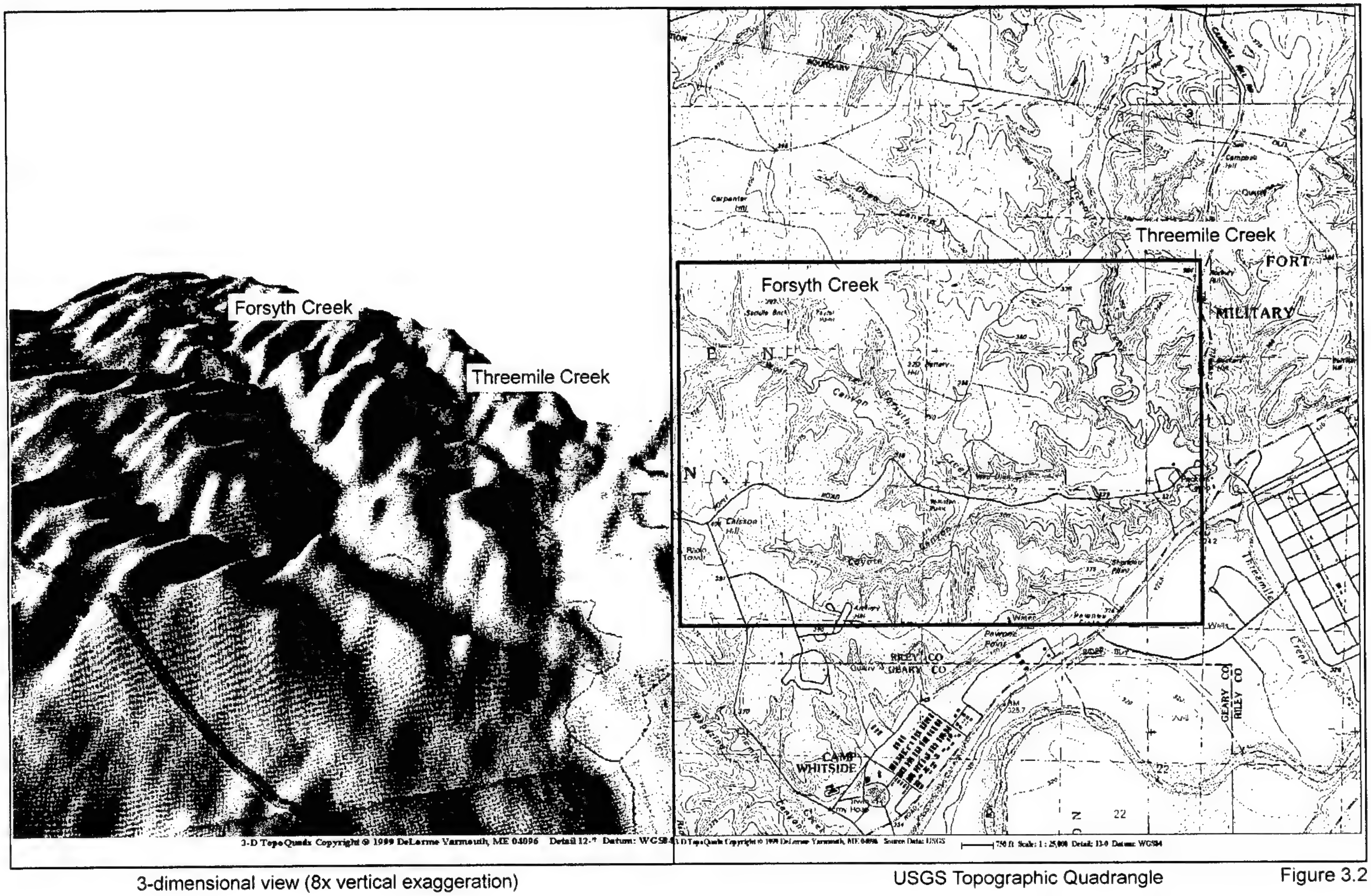
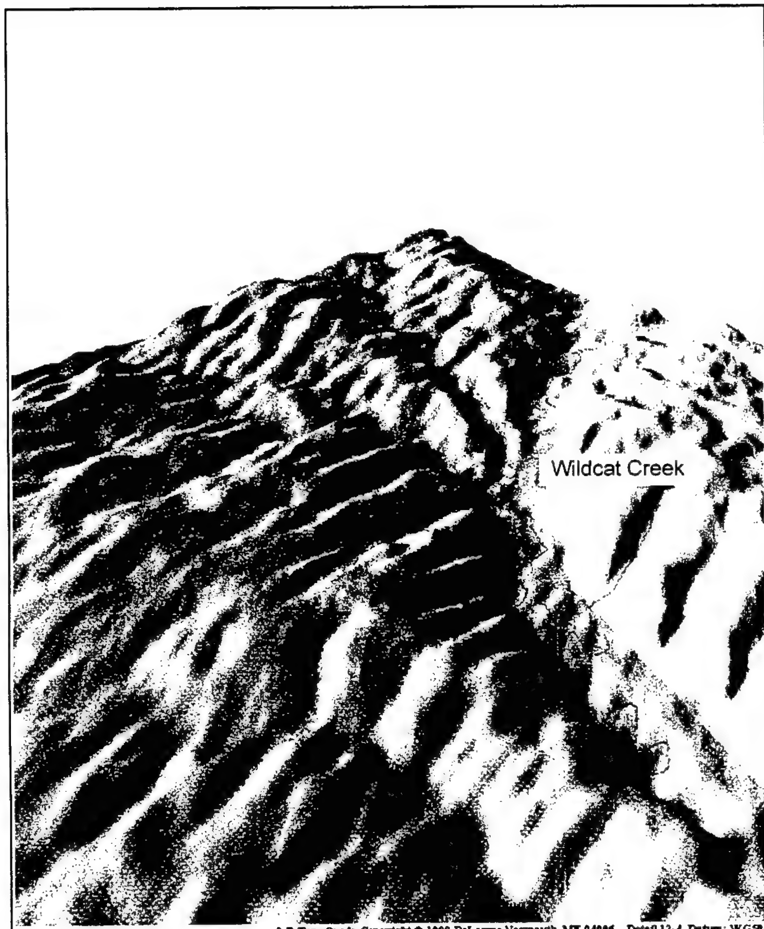
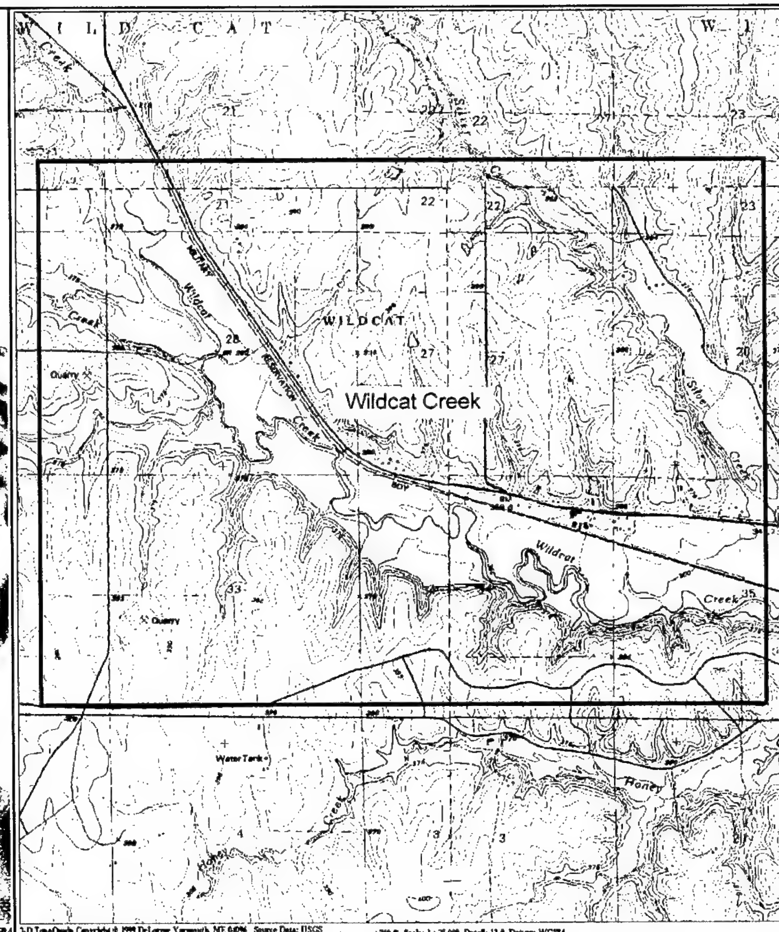


Figure 3.2. Three-dimensional block diagram (left) and corresponding topographic map (right) of Forsyth Creek.

Wildcat Creek



3-dimensional view (8x vertical exaggeration)

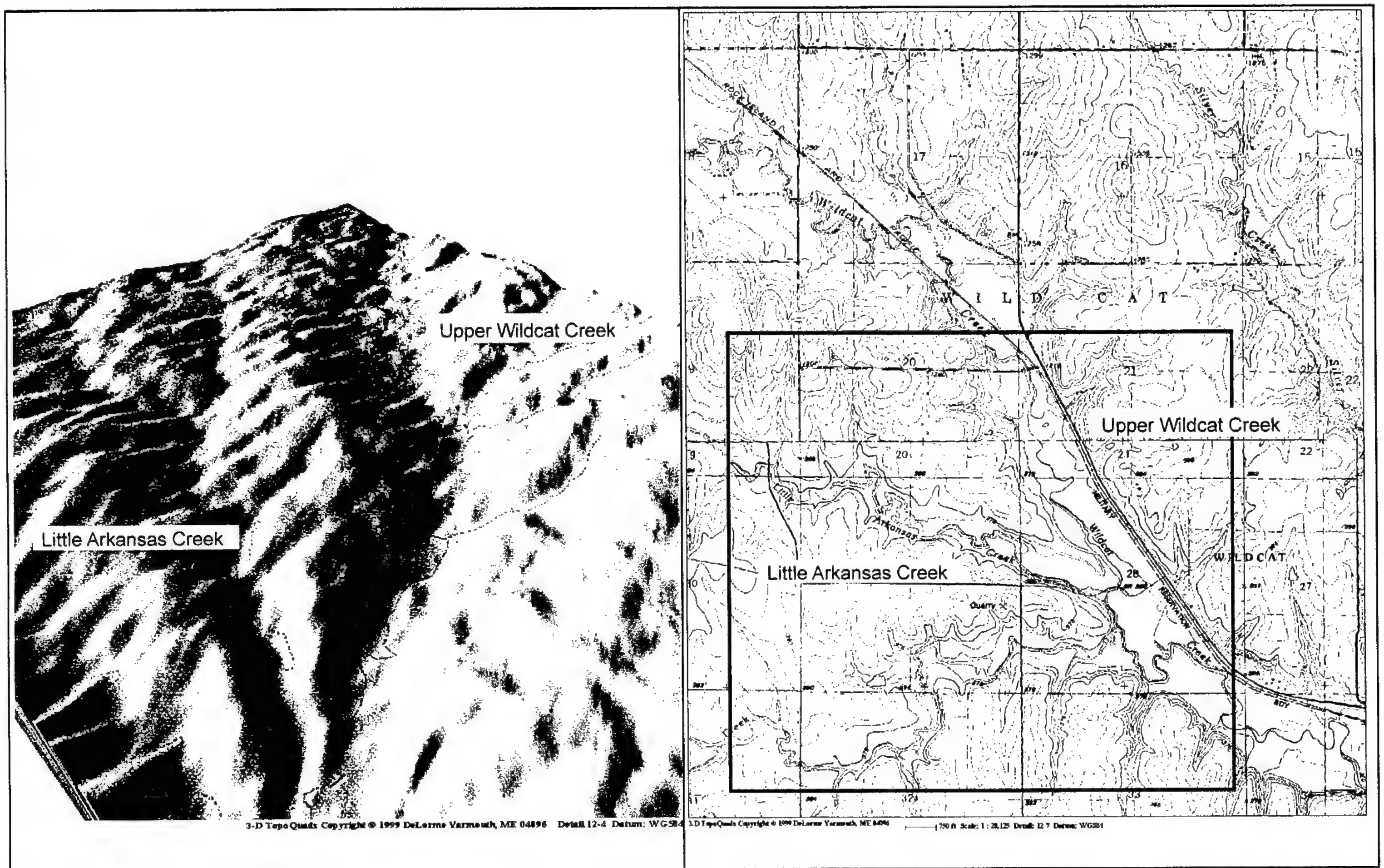


USGS Topographic Quadrangle

Figure 3.3

Figure 3.3. Three-dimensional block diagram (left) and corresponding topographic map (right) of Wildcat Creek.

Upper Wildcat Creek and the Little Arkansas Creek



3-dimensional view (8x vertical exaggeration)

USGS Topographic Quadrangle

Figure 3.4

Figure 3.4. Three-dimensional block diagram (left) and topographic map (rightof Upper Wildcat Creek and Little Arkansas Creek.

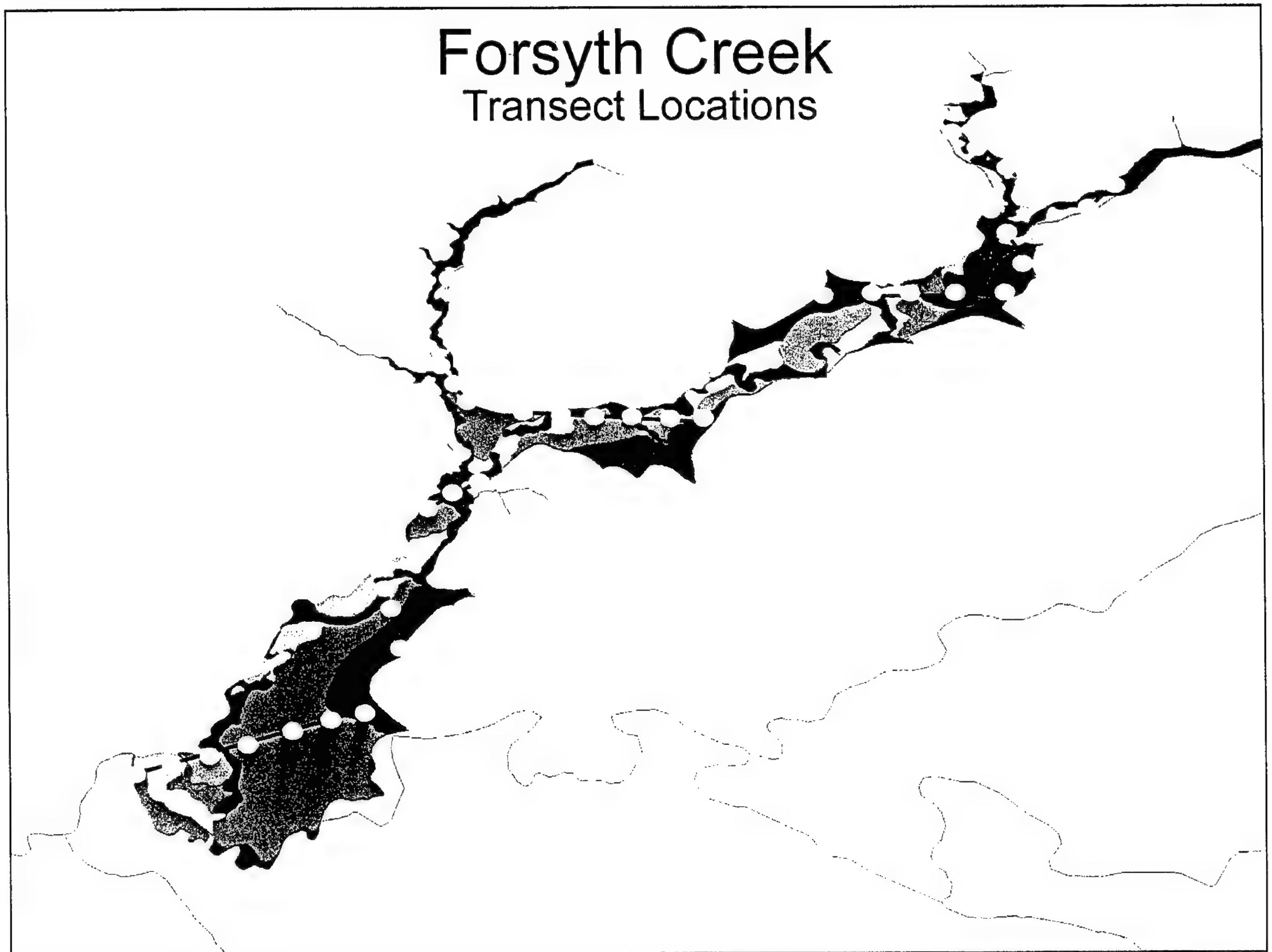


Figure 3.5. Geomorphological sampling locations along transects in Forsyth Creek.

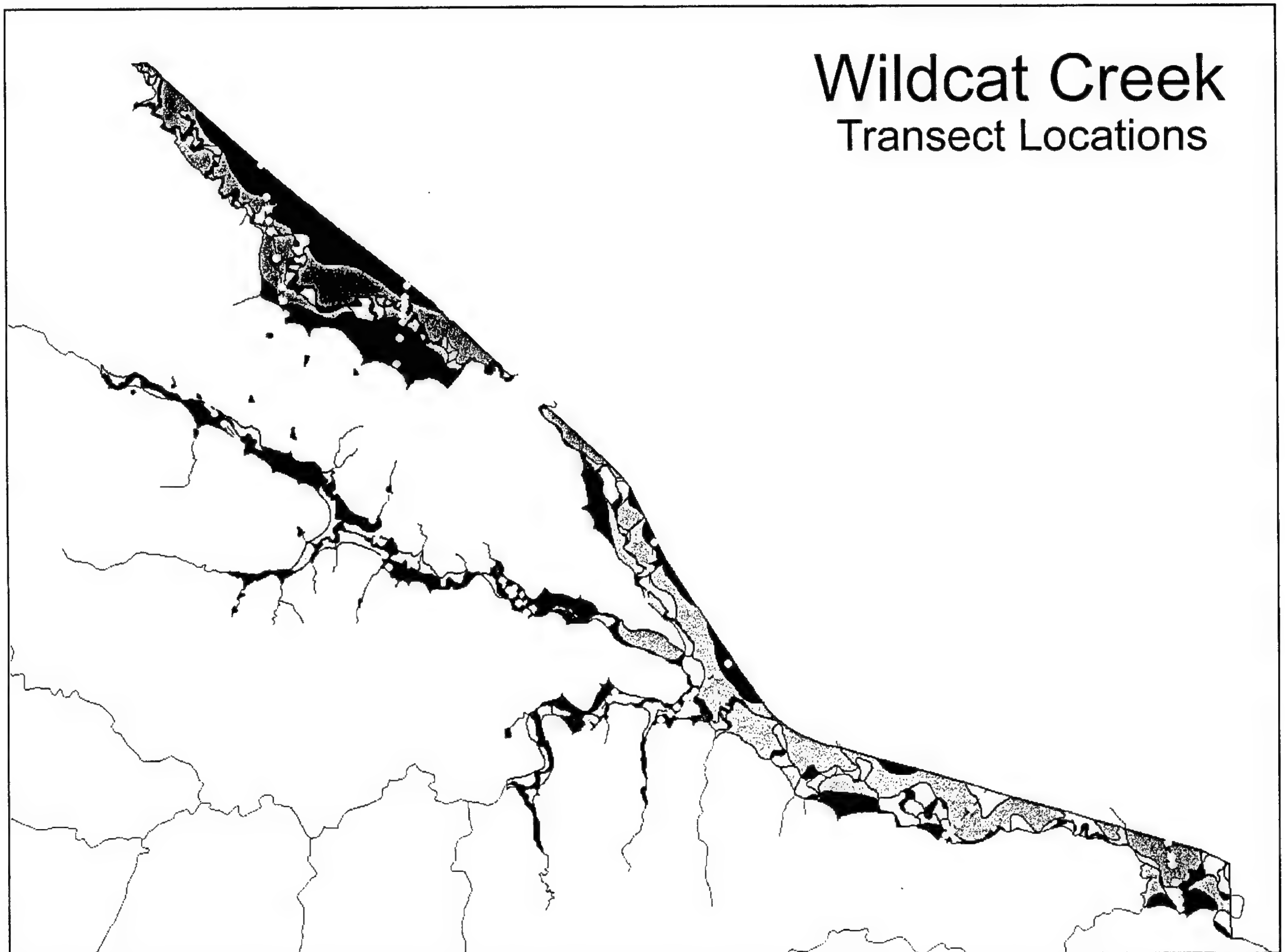


Figure 3.6

Figure 3.6. Geomorphological sampling locations along transects in Wildcat Creek.

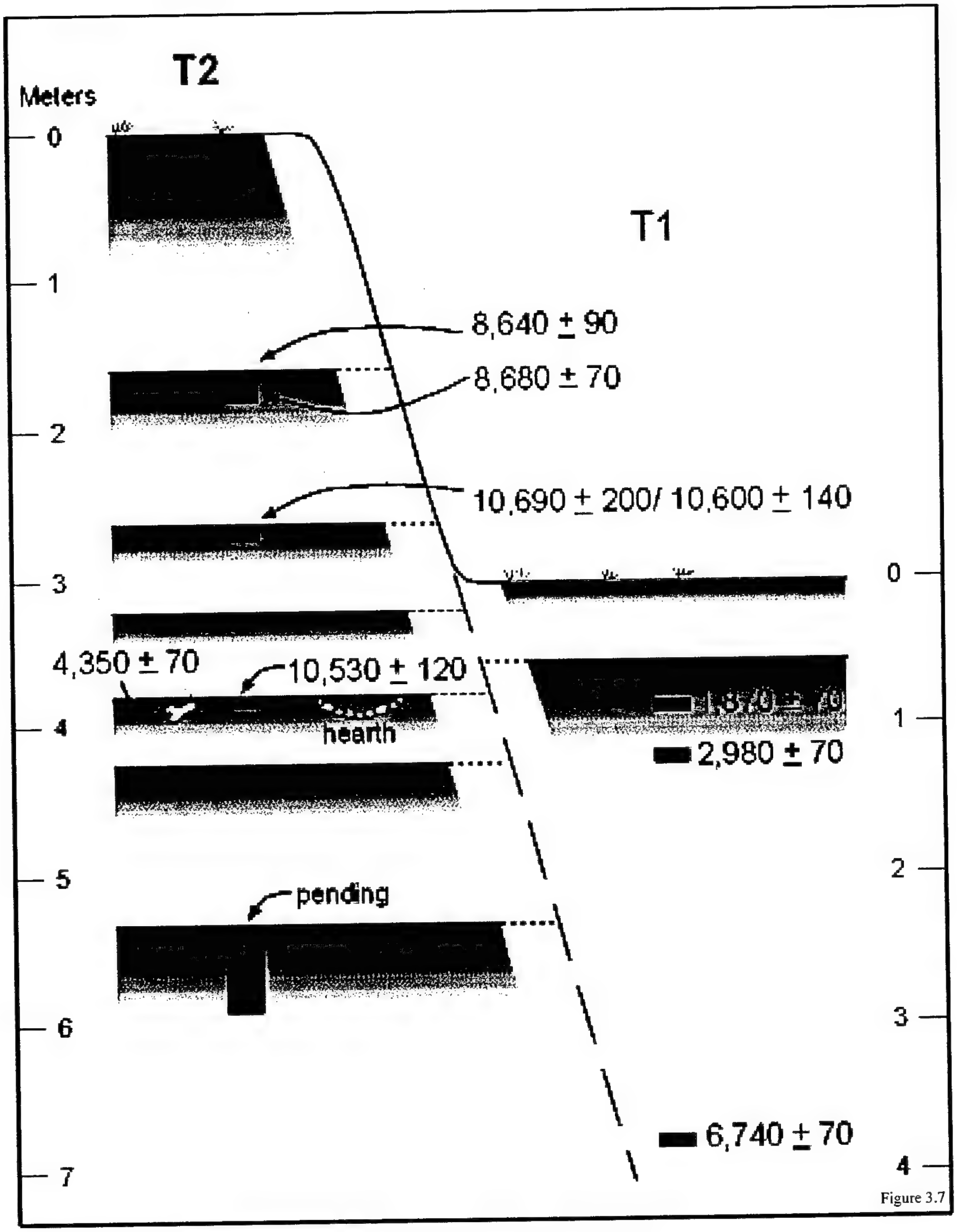
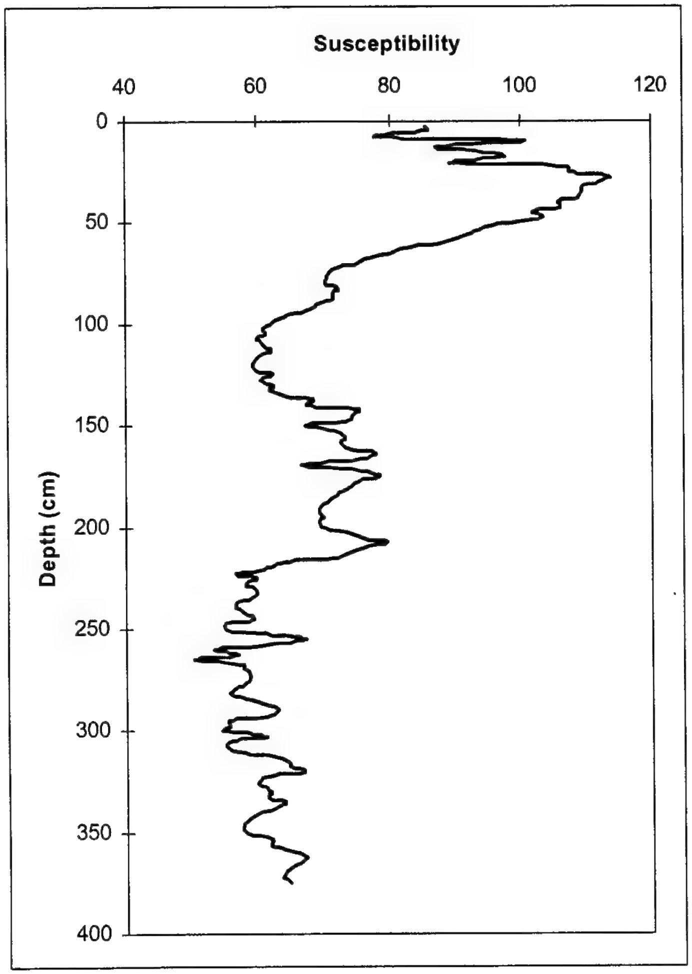


Figure 3.7. Schematic cross-section showing relationship between the fills of the T2 and T1 surfaces (terraces) at Site FR4 in Forsyth Creek, near the confluence with Three Mile Creek. Note dated paleosols in both terrace formations and deeply buried cultural material in the older T2 terrace.



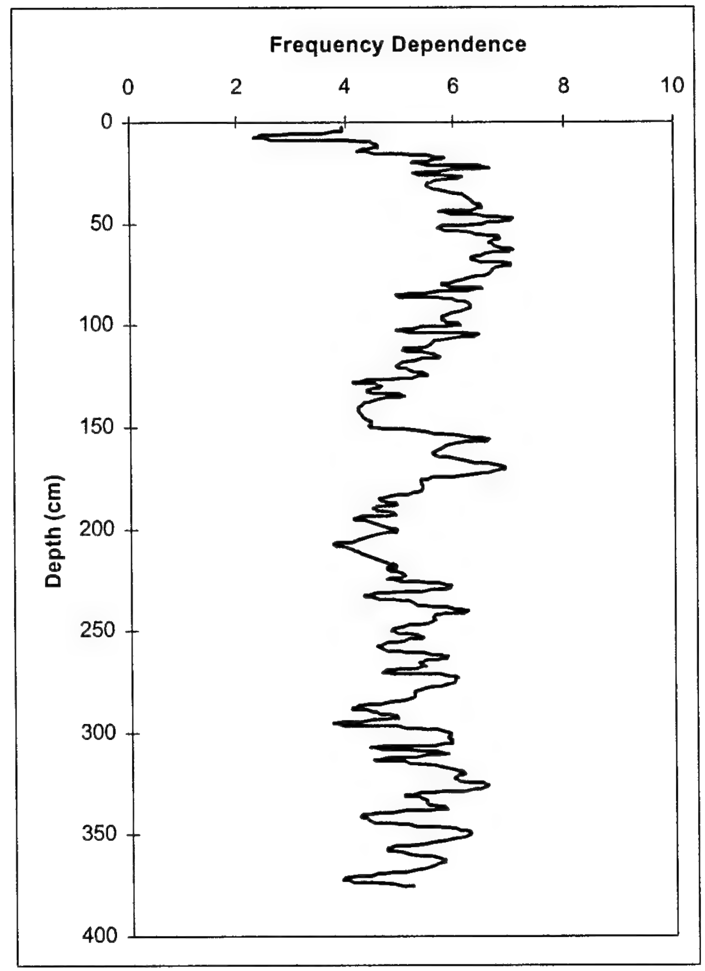


Figure 3.8. Magnetic susceptibility curve (left) and frequency dependence curve (right) for Forsyth Creek (FR4) T2 fill

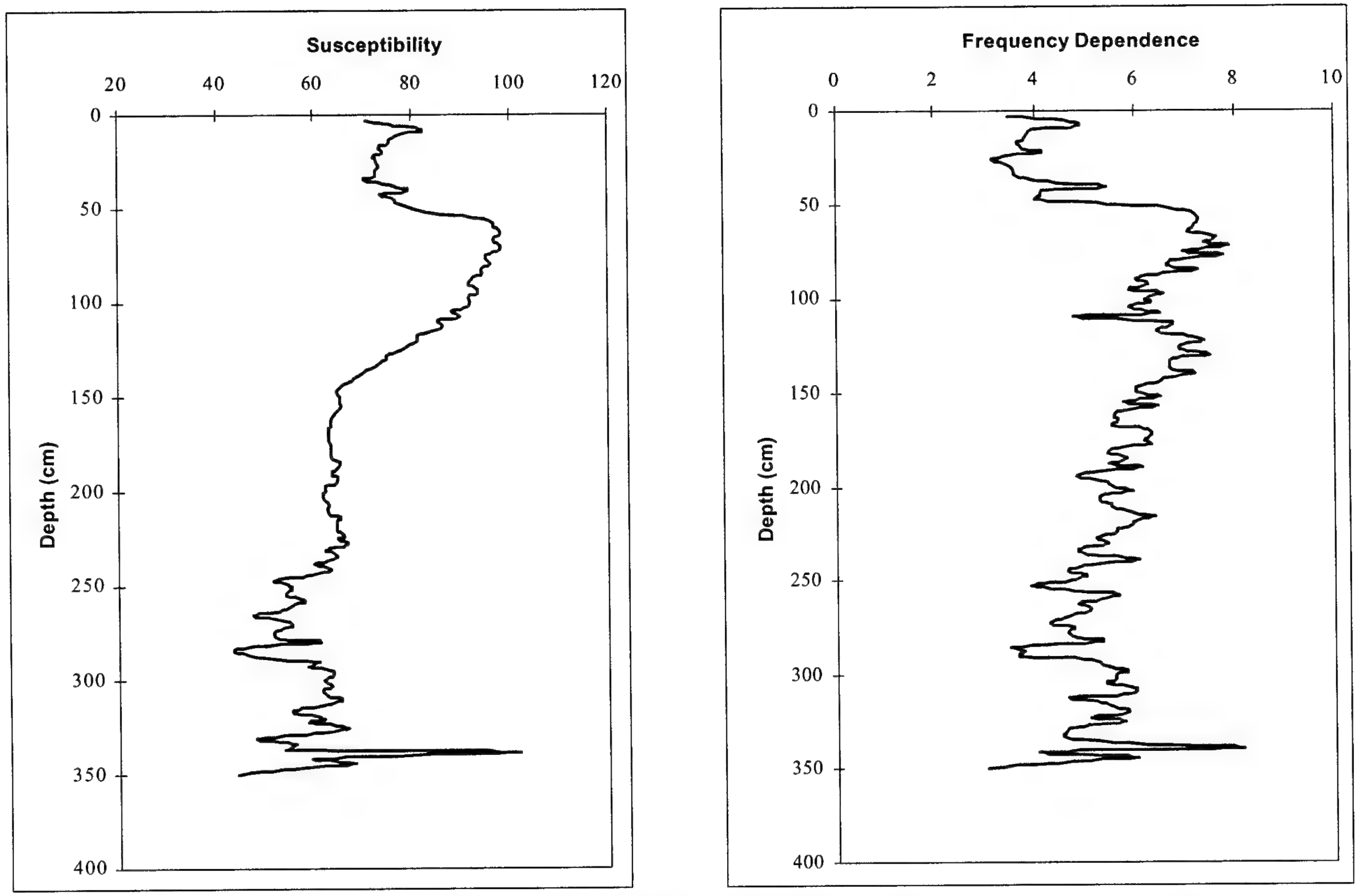


Figure 3.9. Magnetic susceptibility curve (left) and frequency dependence curve (right) for Forsyth Creek (FR4) T1 fill.

Figure 3.10. Frequency of Grass Short Cells and Arboreal Phytoliths from FR4 (T2)
(fr4bb%)

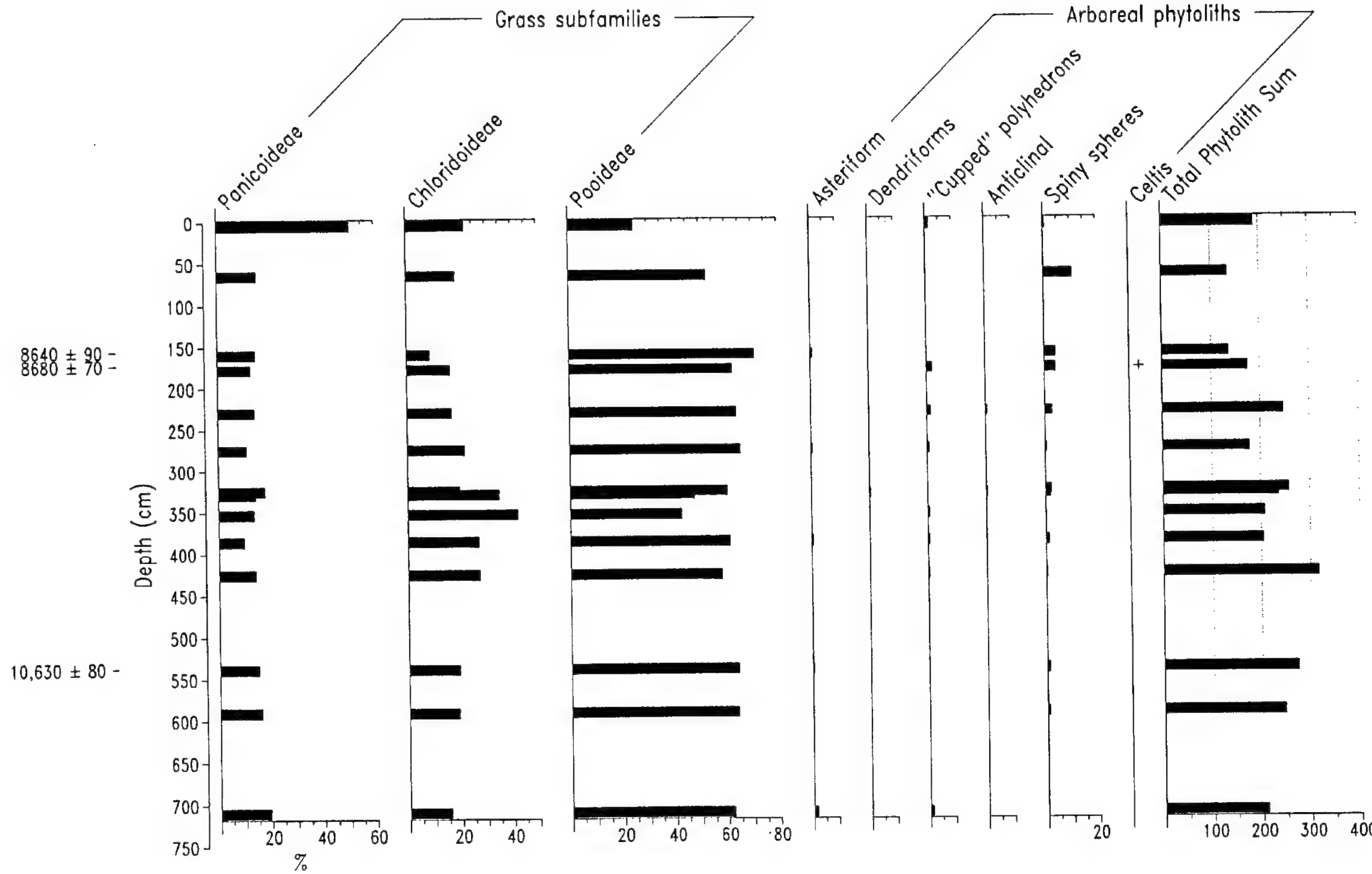


Figure 3.10. Frequency of grass short cells and arboreal phytoliths from Forsyth Creek (FR4), T2 fill.

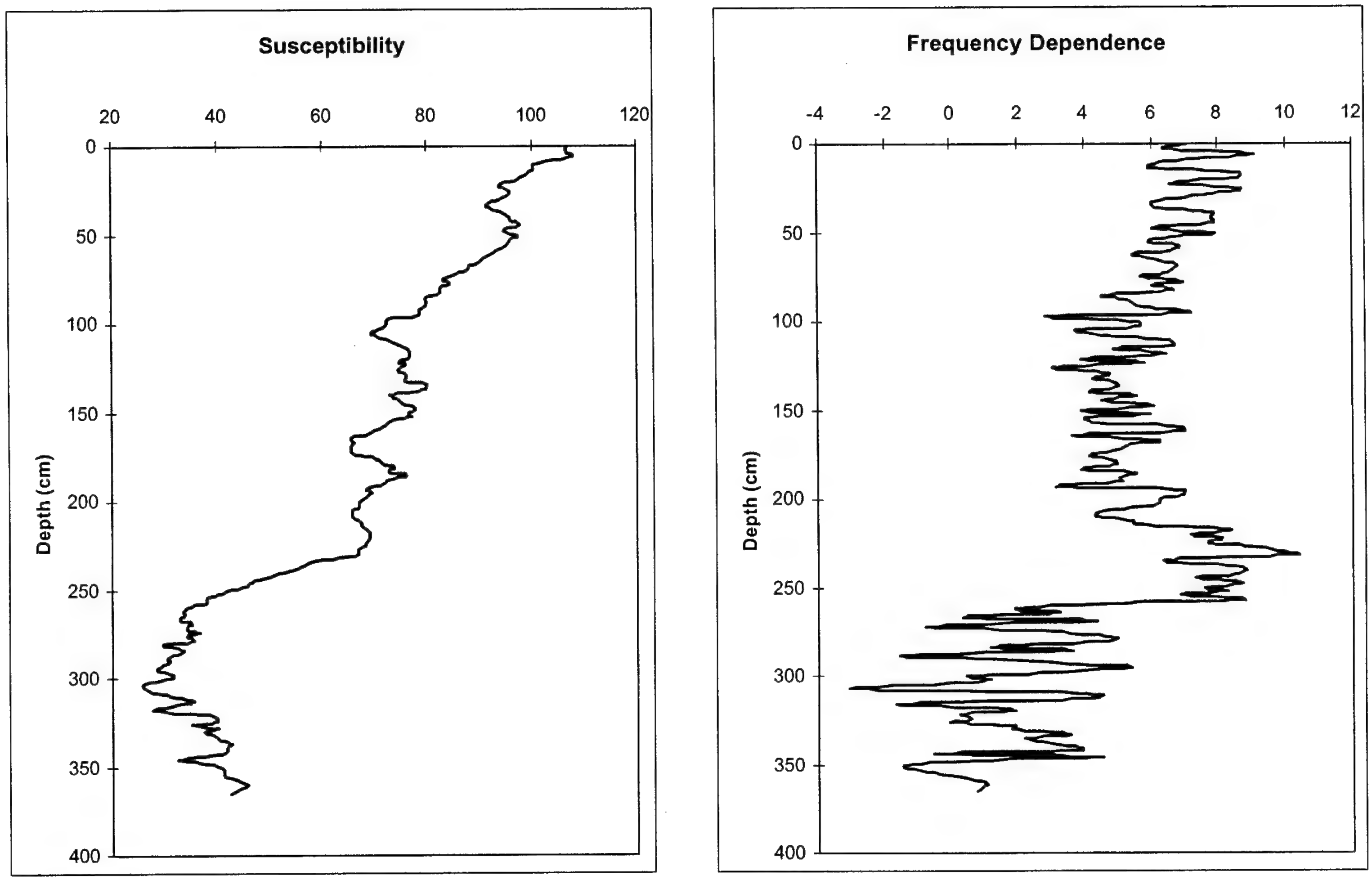


Figure 3.11. Magnetic susceptibility curve (left) and frequency dependence curve (right) for Wildcat Creek (WC1), T1 fill.

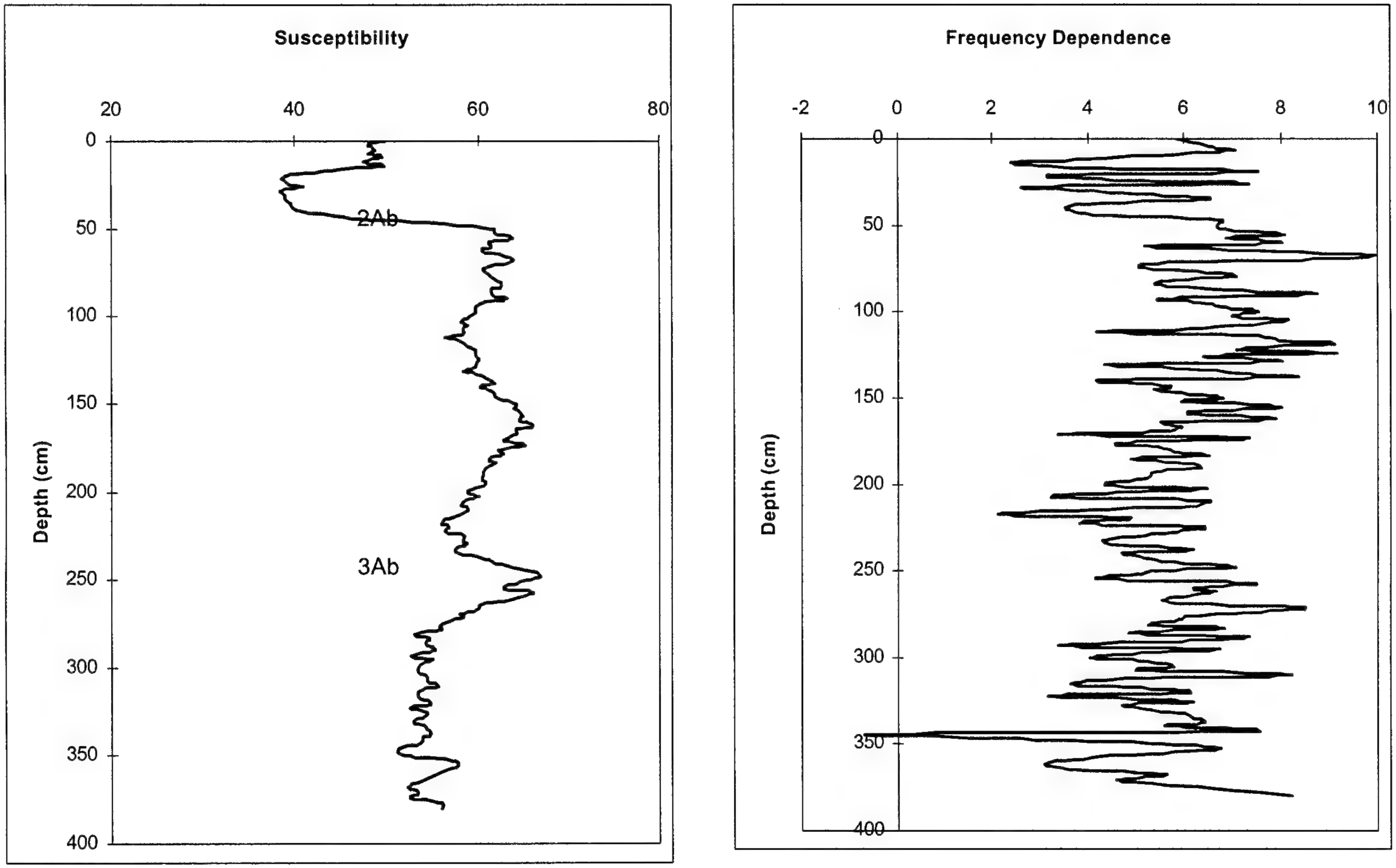


Figure 3.12. Magnetic susceptibility curve (left) and frequency dependence curve (right) for Wildcat Creek (WC1), T2 fill.

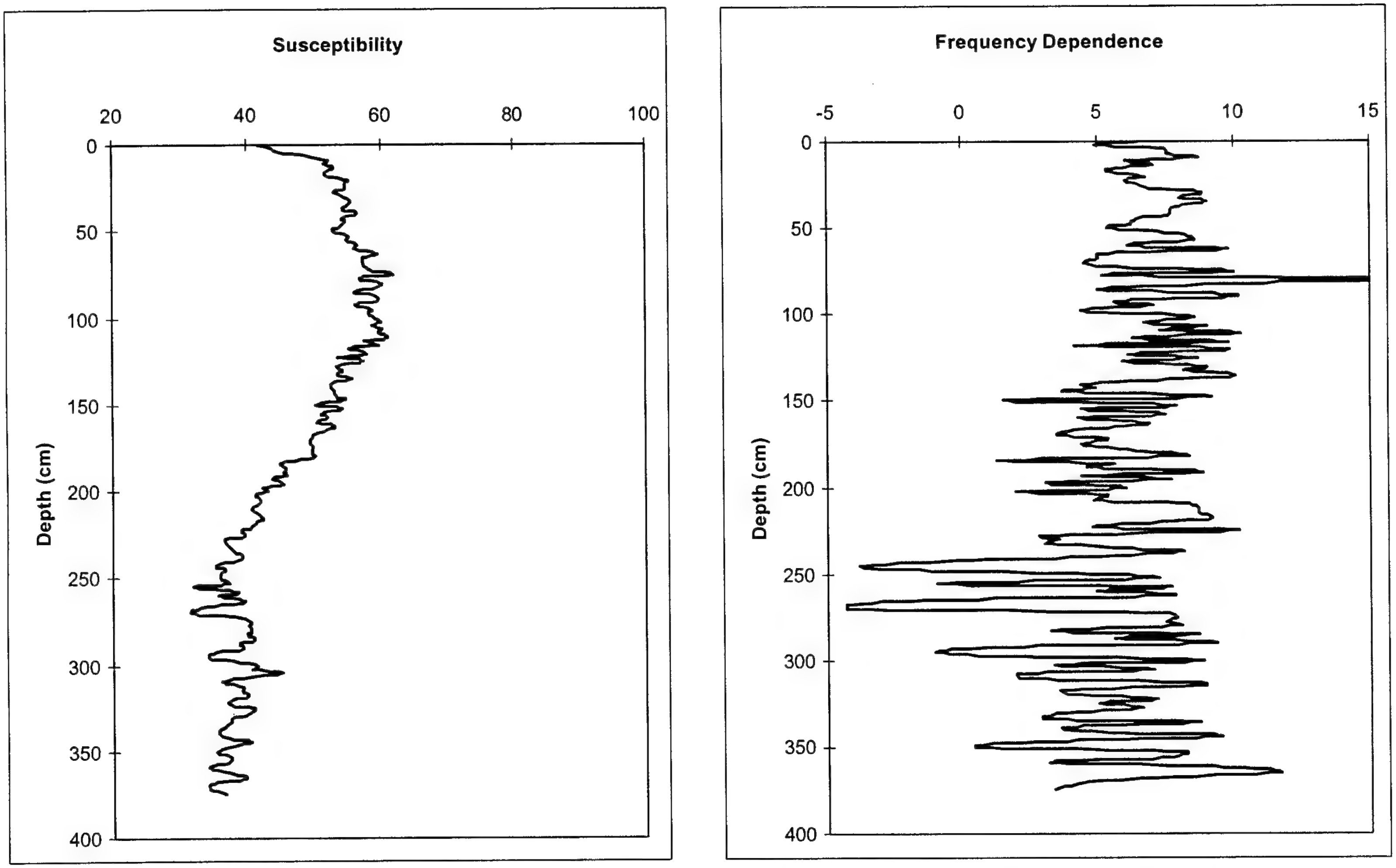


Figure 3.13. Magnetic susceptibility curve (left) and frequency dependence curve (right) for Wildcat Creek (WC4), T2 fill.

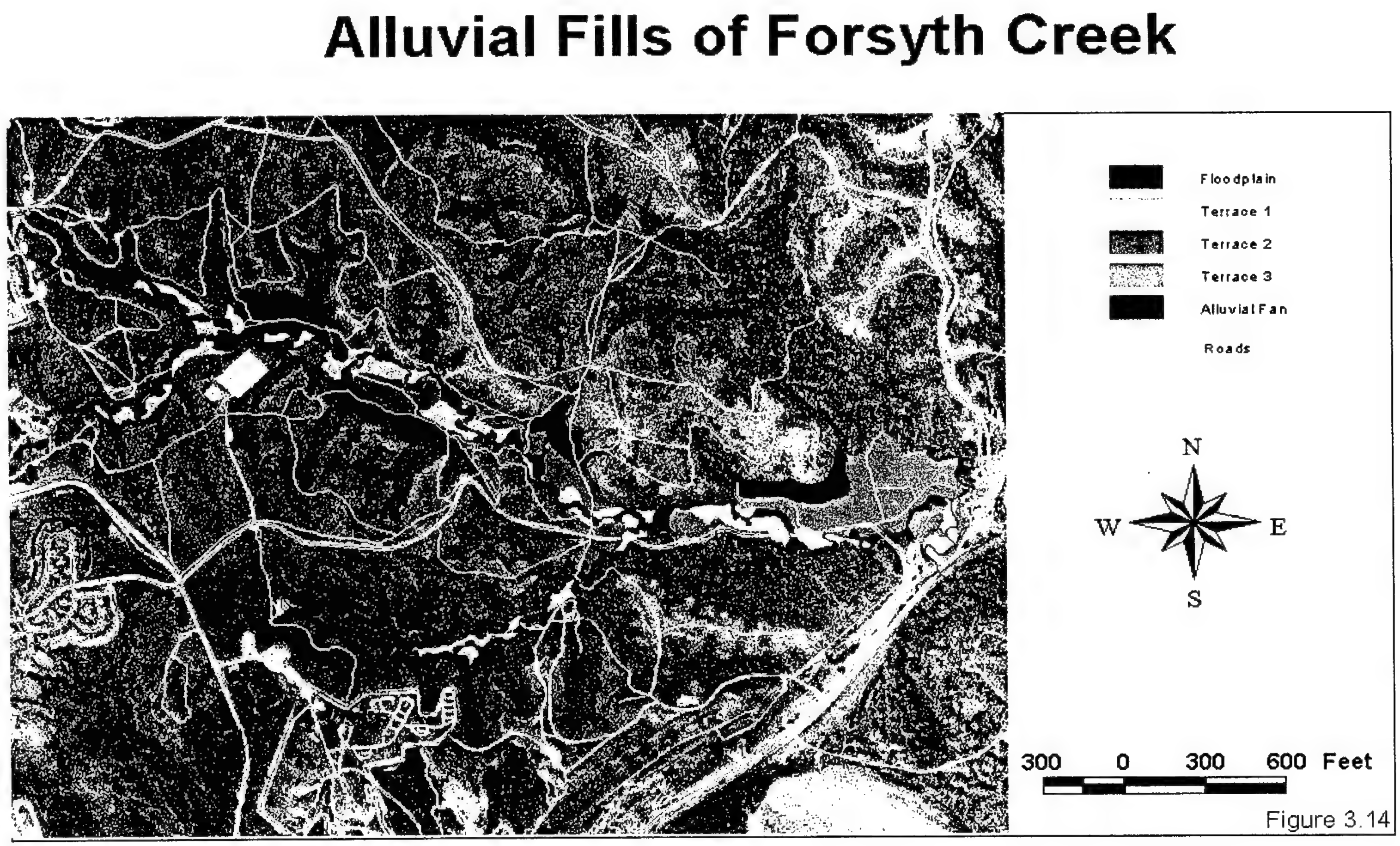


Figure 3.14. Aerial photograph of Forsyth Creek showing color overlays of five different alluvial surfaces.

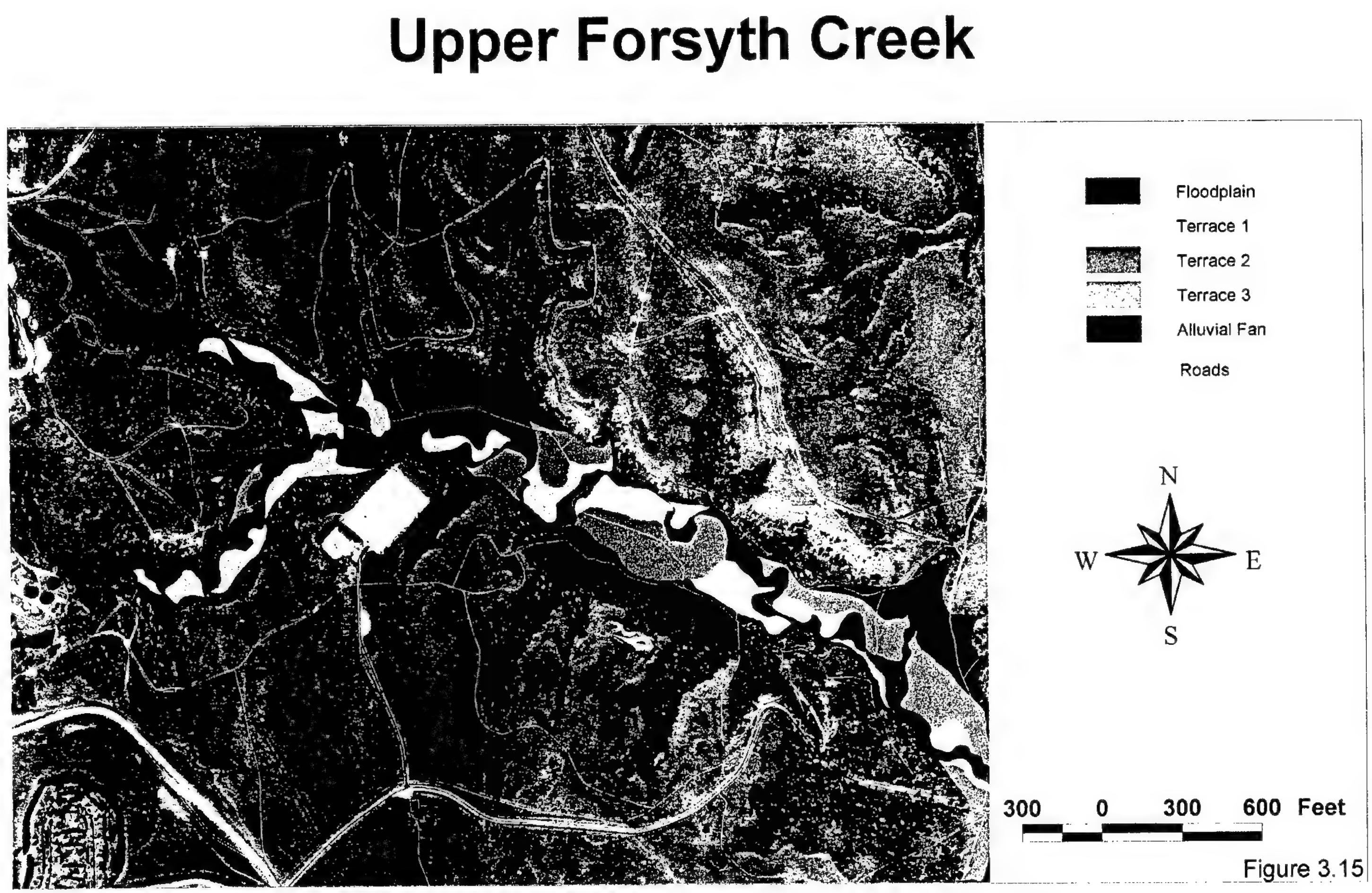


Figure 3.15. Aerial photograph of Upper Forsyth Creek showing color overlays of five different alluvial surfaces.

Williston Point - Forsyth Creek

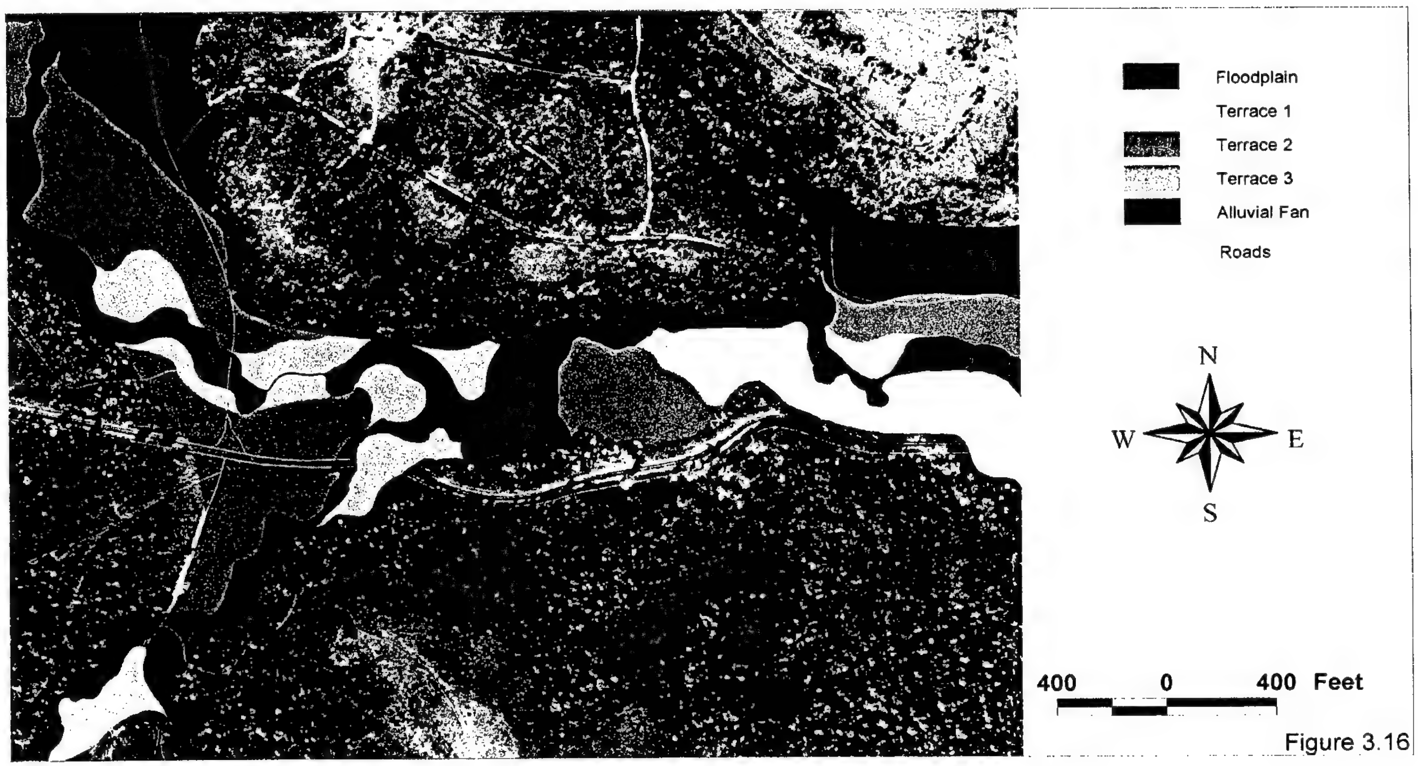


Figure 3.16. Aerial photograph of Williston Point locality, Forsyth Creek, showing color overlays of five different alluvial surfaces.

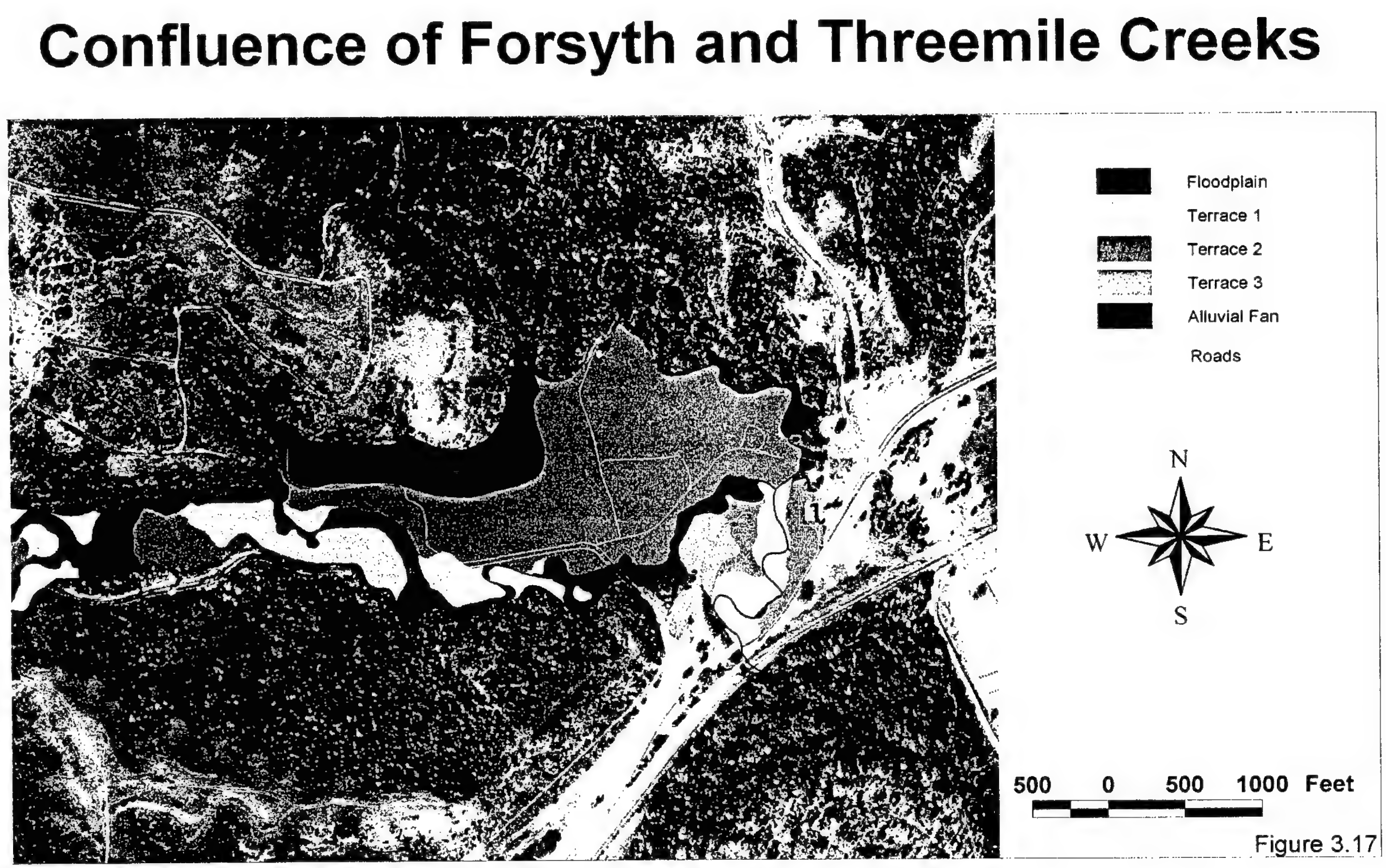
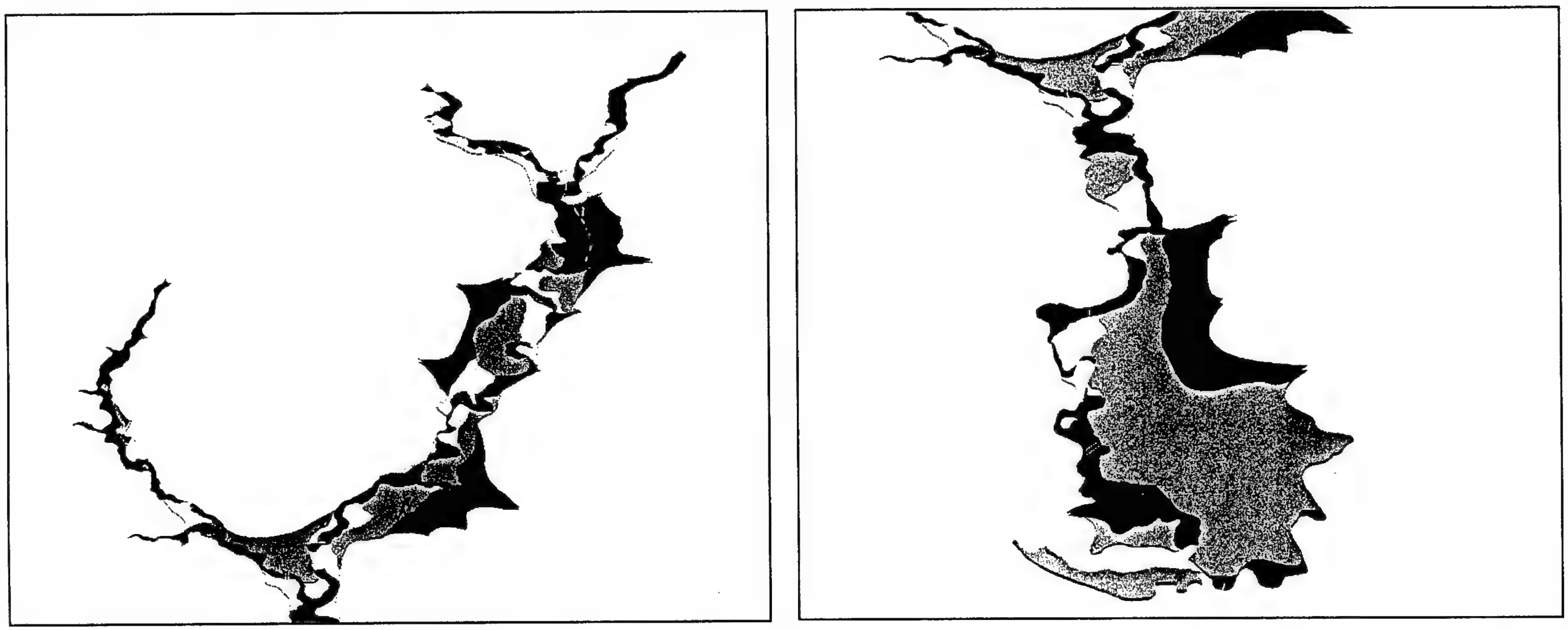


Figure 3.17. Aerial photograph of Forsyth Creek/Threemile Creek confluence, showing color overlays of five different alluvial surfaces.

Forsyth Creek



A. Upper　　B. Lower　　Figure 3.18

Figure 3.18. Oblique relief images of Upper and Lower Forsyth Creek showing different alluvial fills.

Forsyth Creek

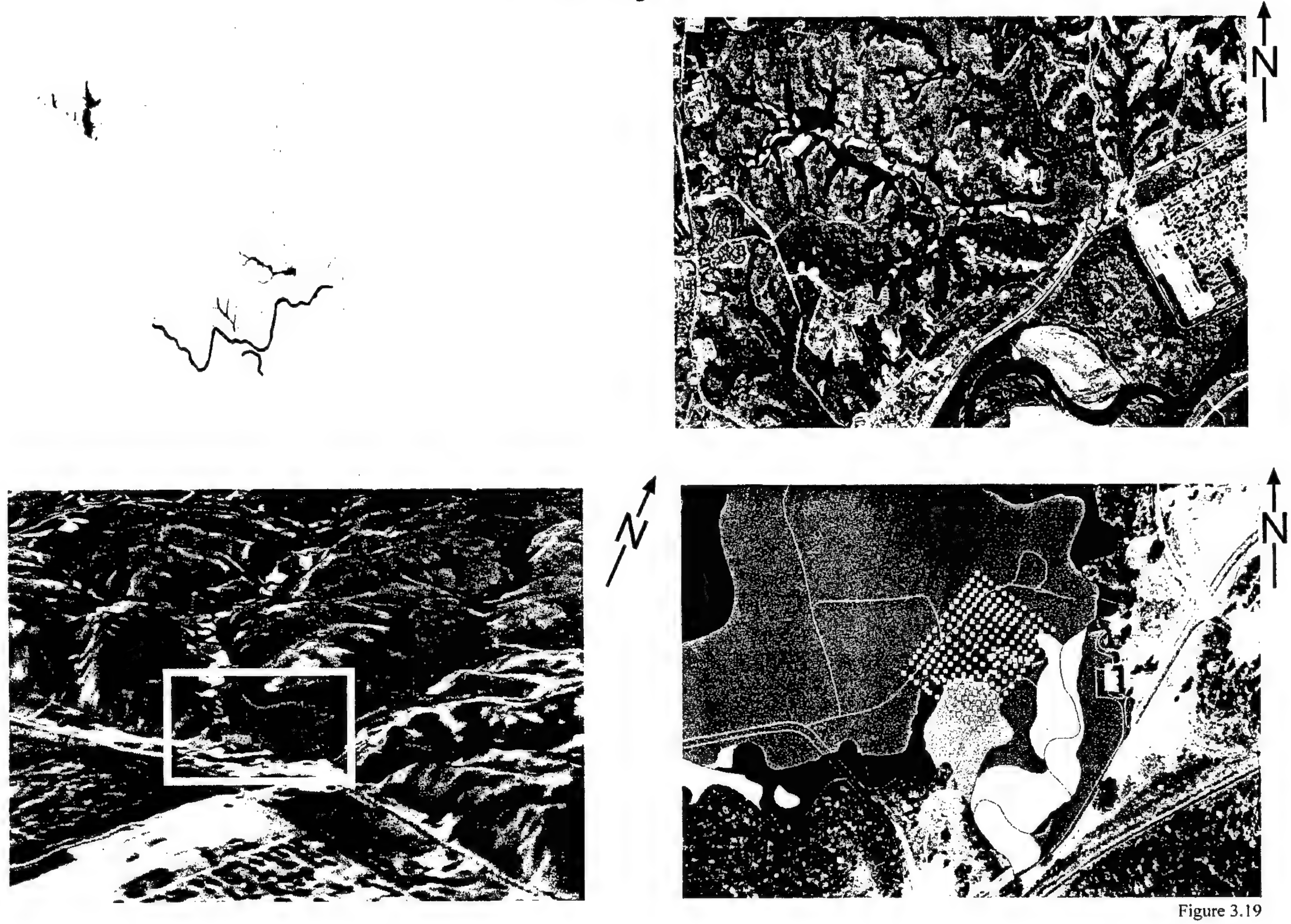


Figure 3.19. High-resolution coring area at Forsyth Creek/Three Mile Creek confluence locality.

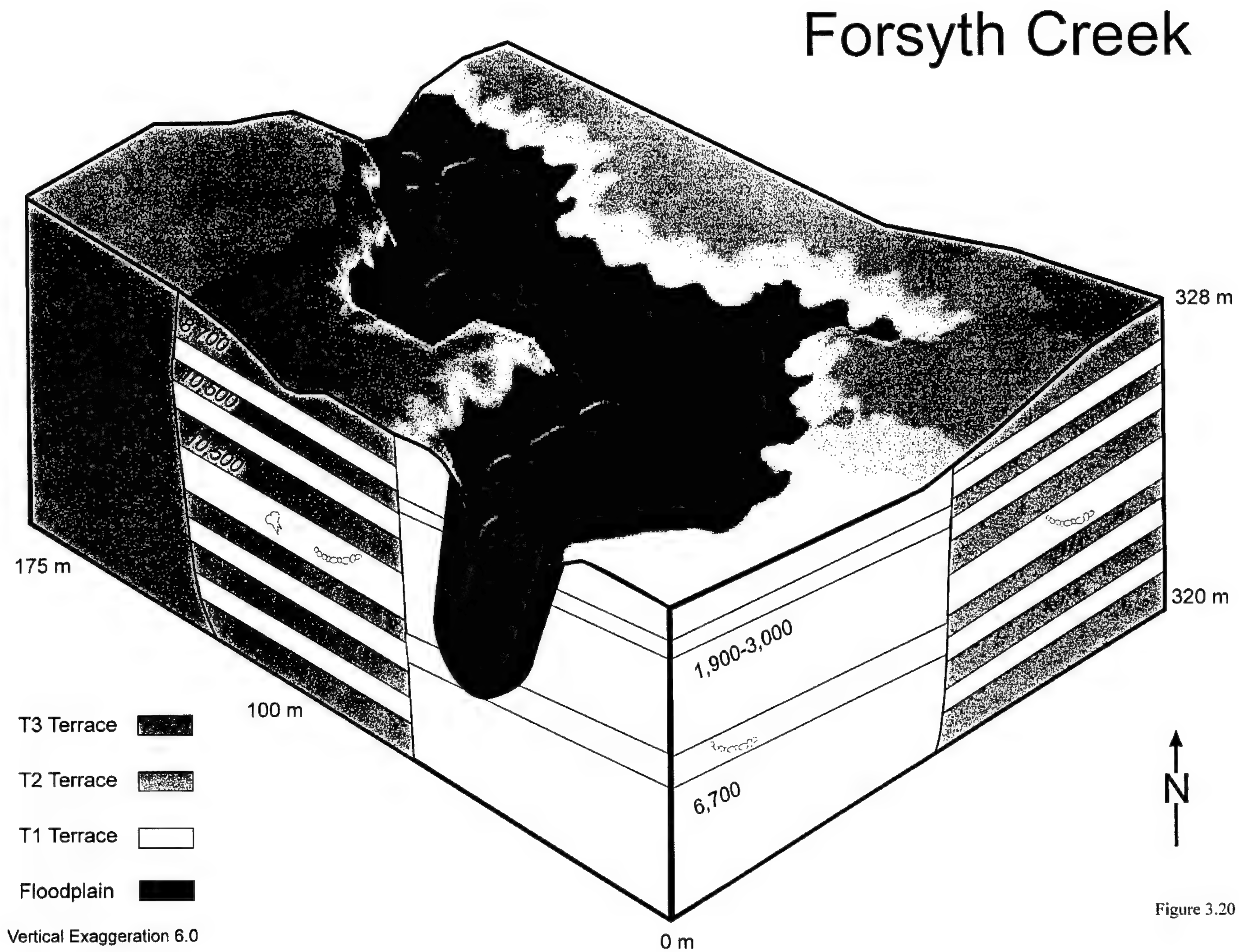


Figure 3.20. 3-dimensional block diagram of Forsyth Creek/Three Mile Creek confluence locality.

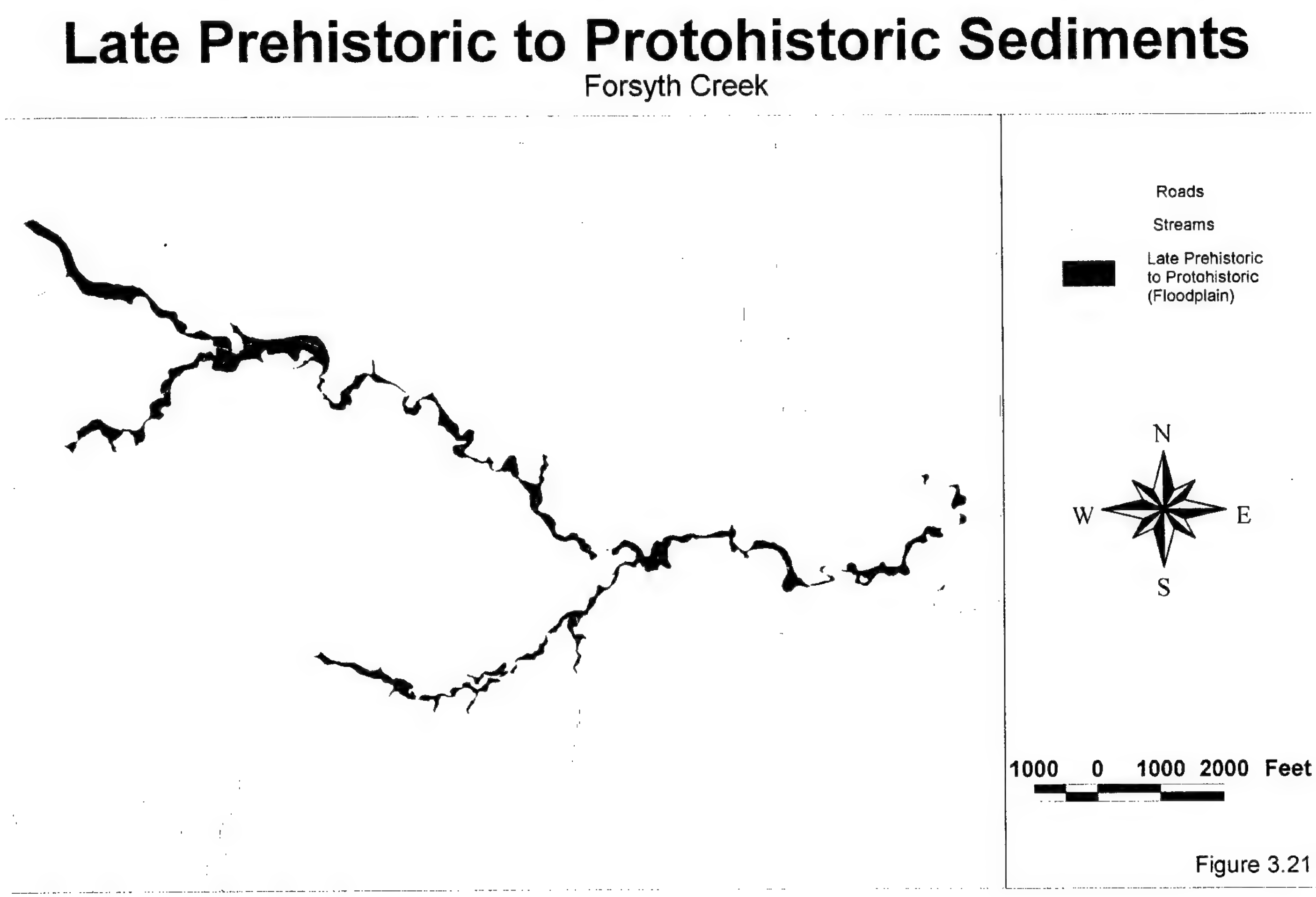


Figure 3.21. Late Prehistoric to Protohistoric sediments along Forsyth Creek.

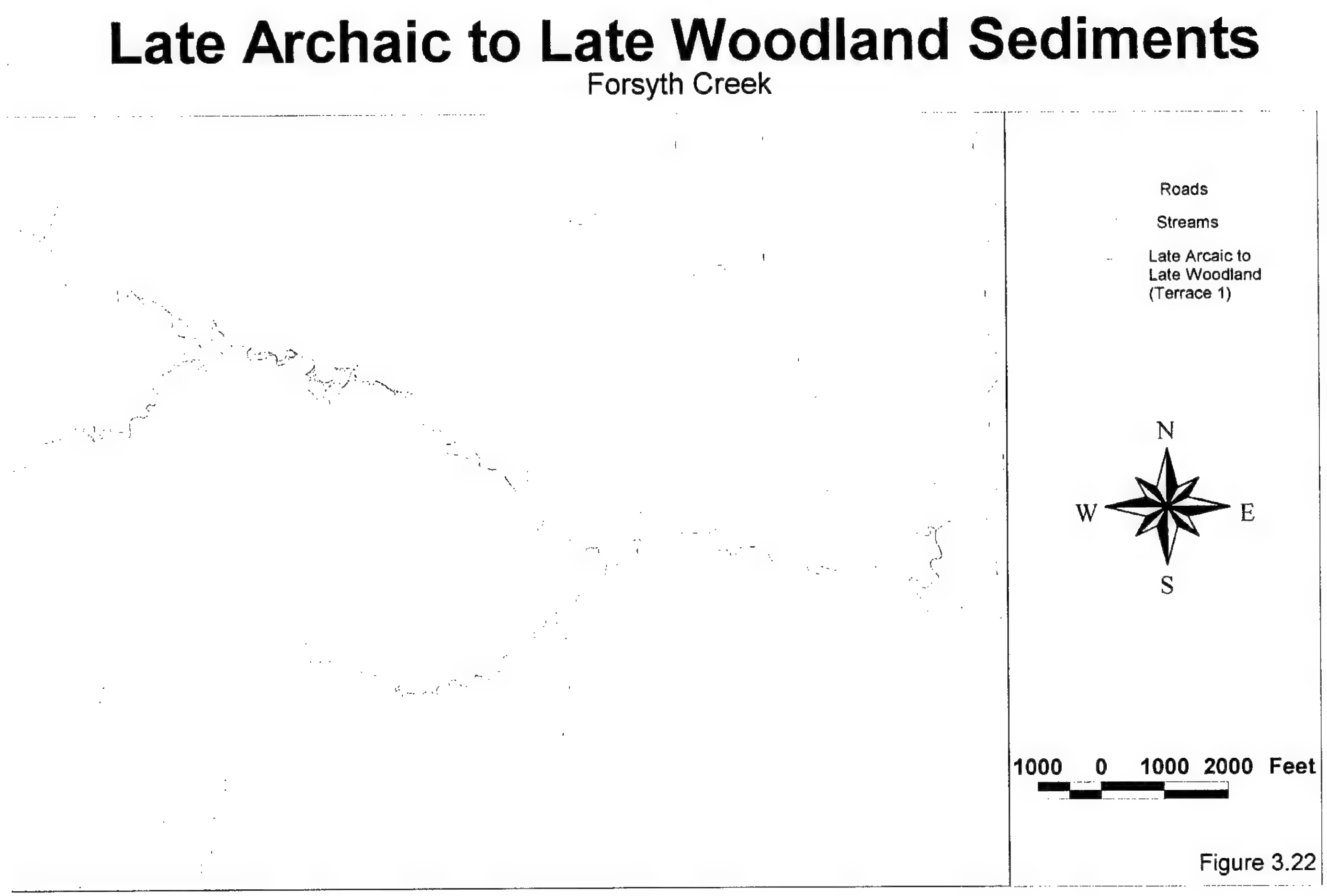


Figure 3.22. Late Archaic to Late Woodland sediments along Forsyth Creek.

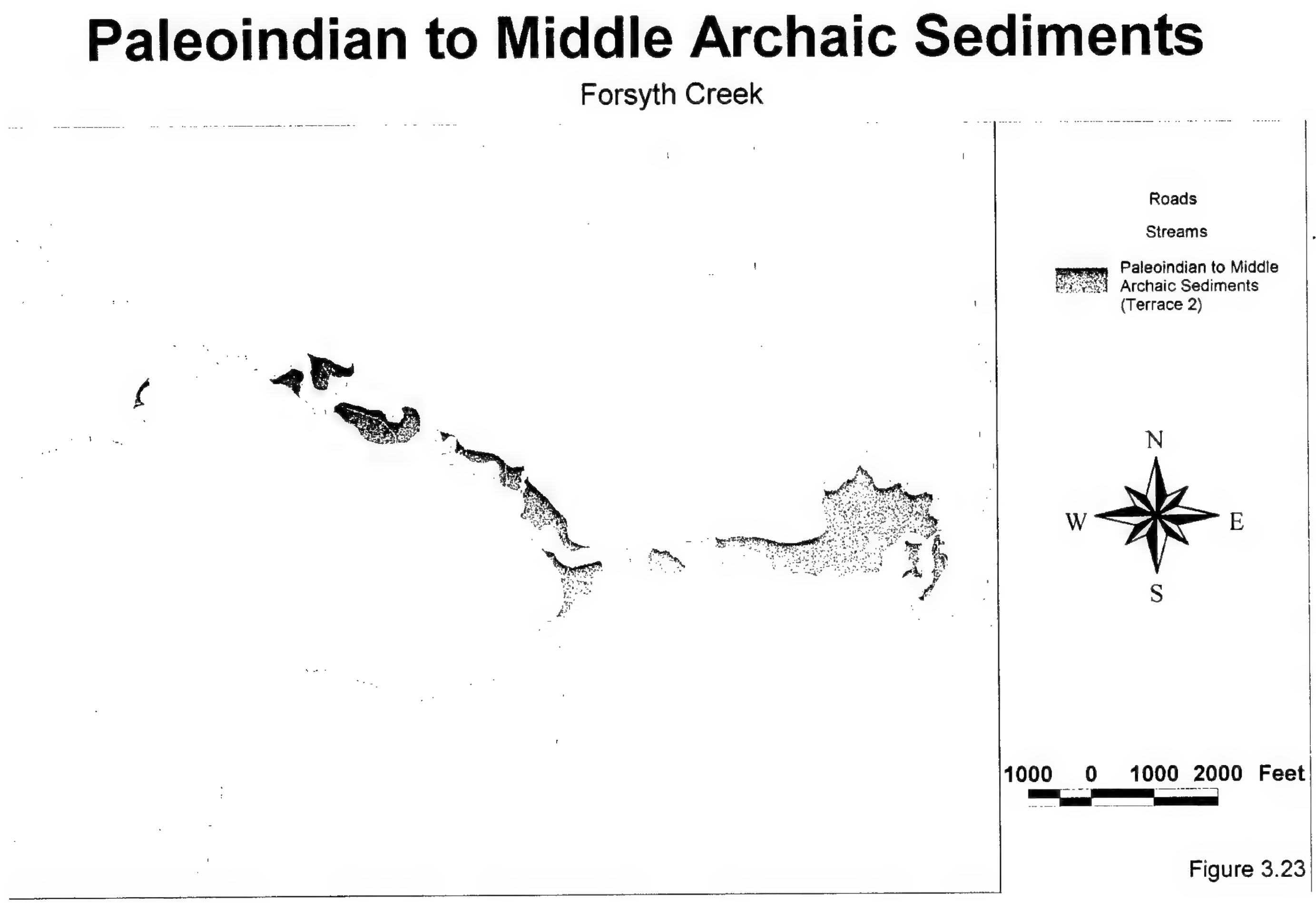


Figure 3.23. Paleoindian to Middle Archaic sediments along Forsyth Creek.

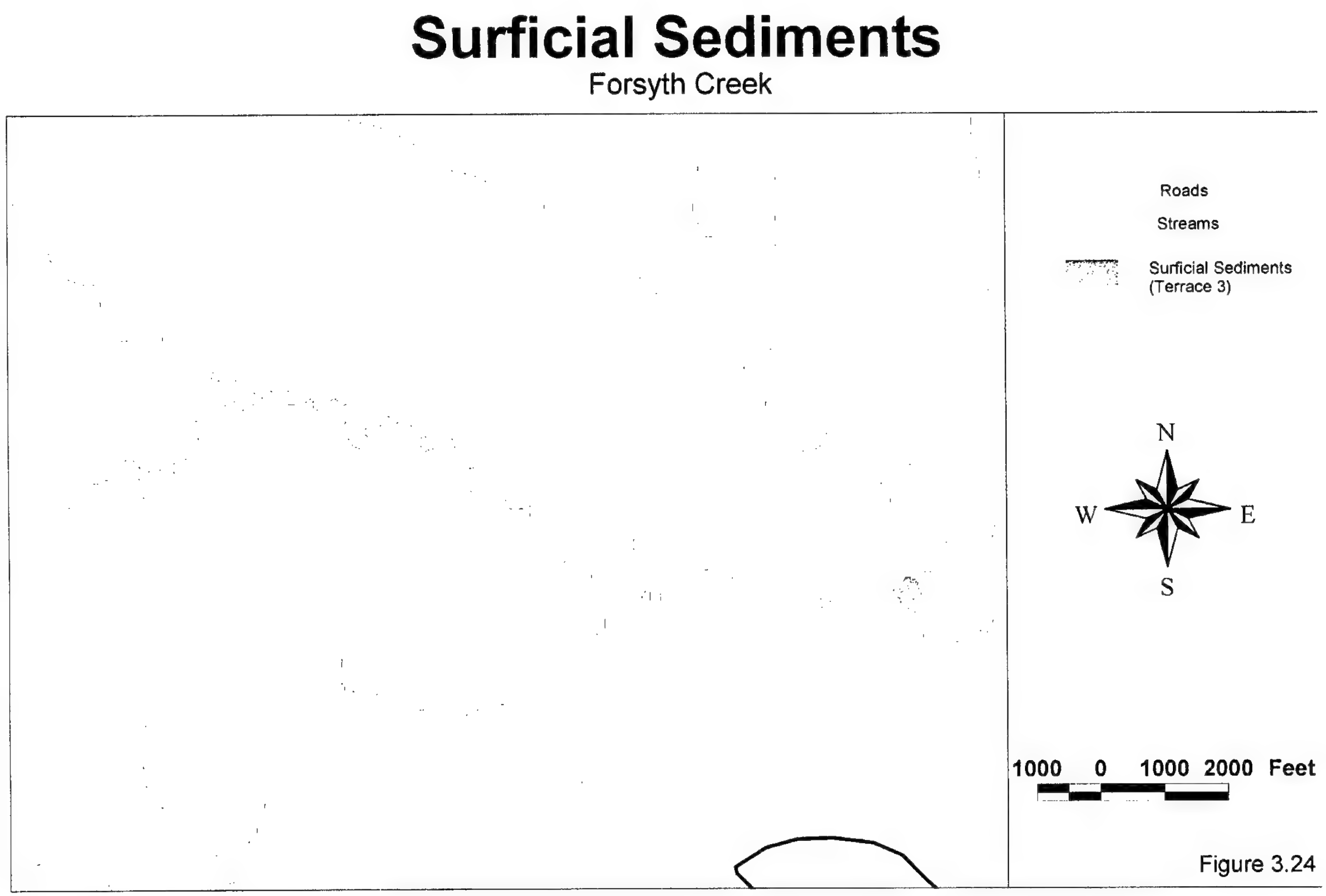


Figure 3.24. Surficial sediments along Forsyth Creek.

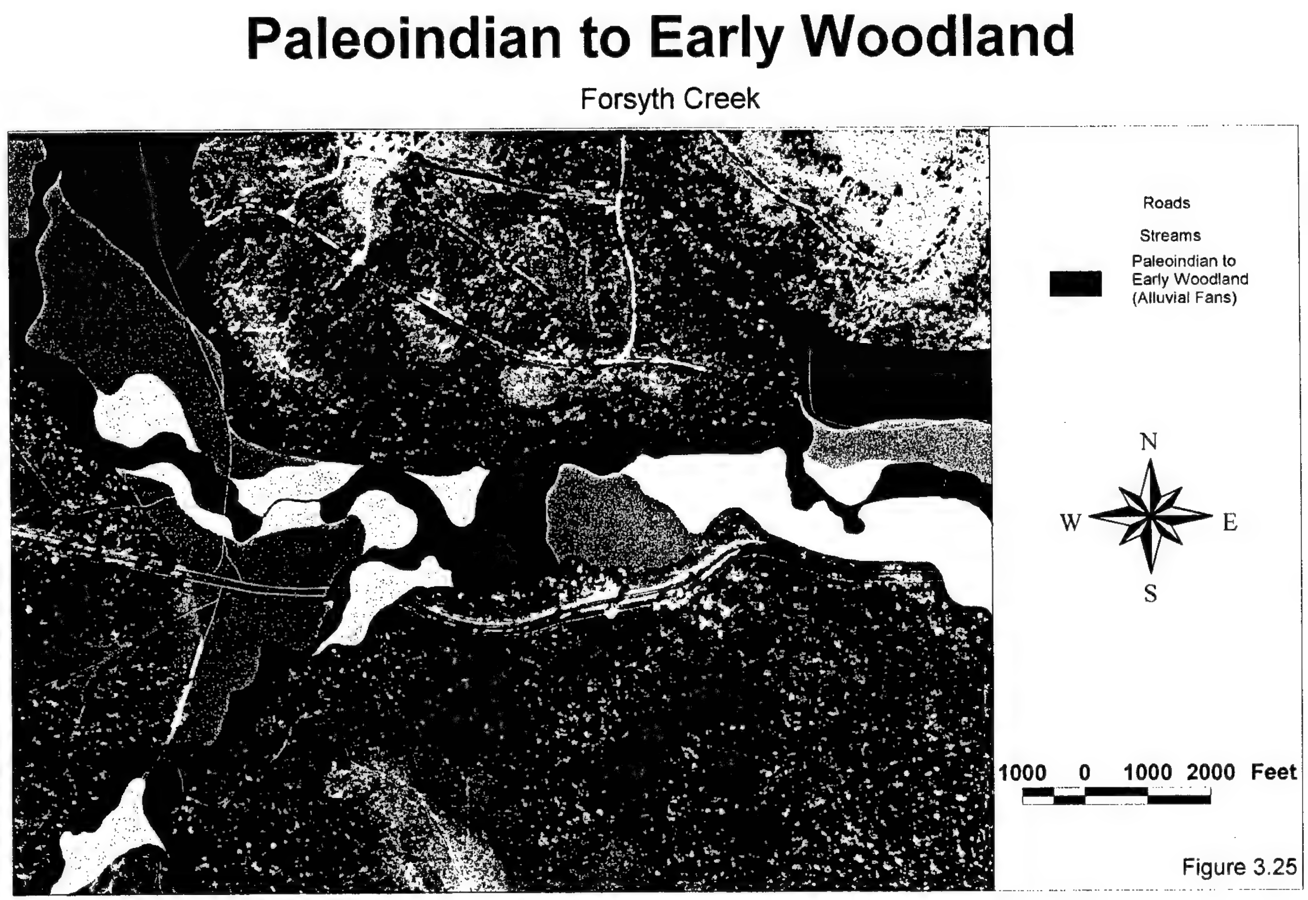


Figure 3.25. Paleoindian to Early Woodland (alluvial fan) sediments along Forsyth Creek.

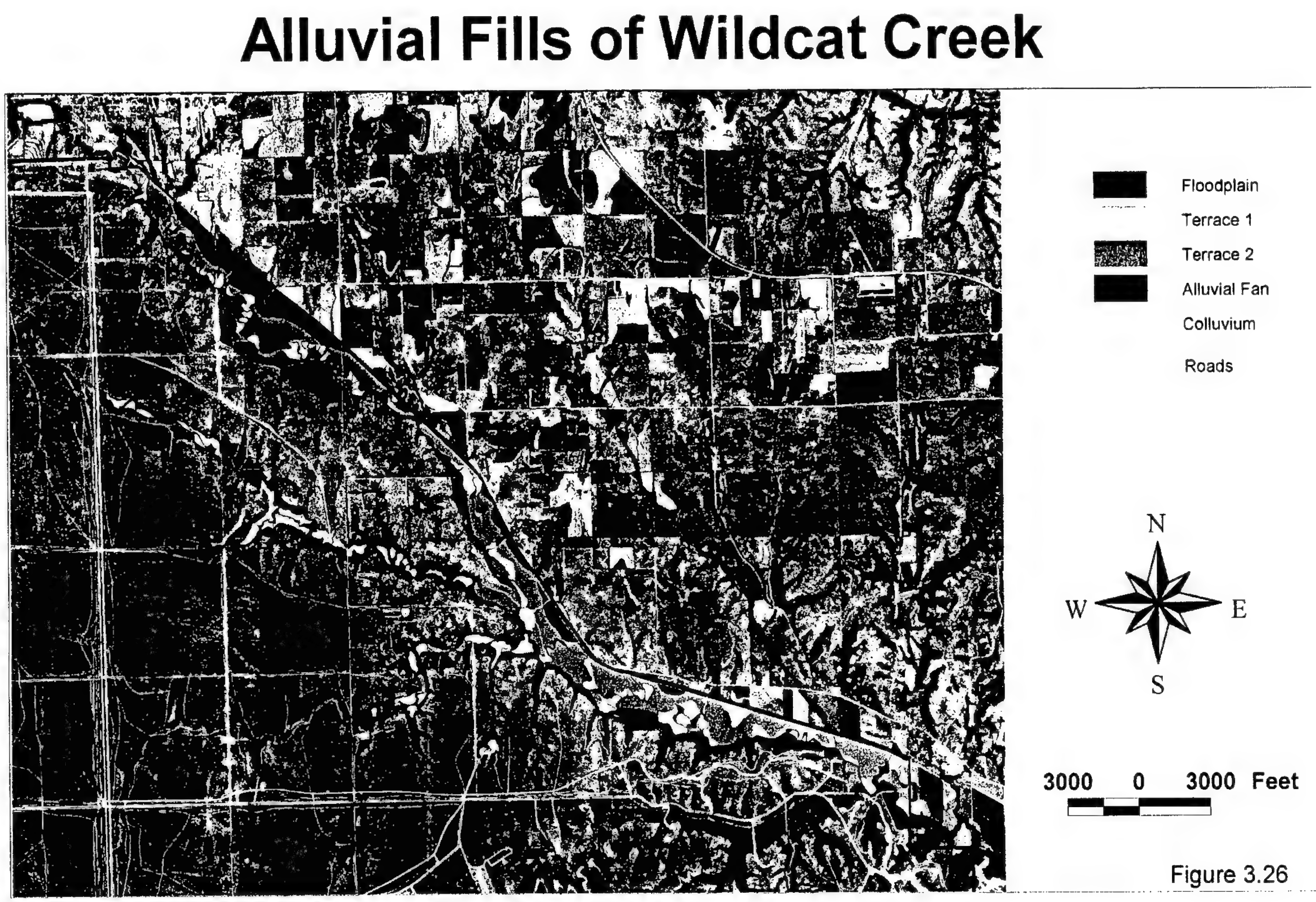


Figure 3.26. Aerial photograph of Wildcat Creek showing color overlays of five different alluvial surfaces.

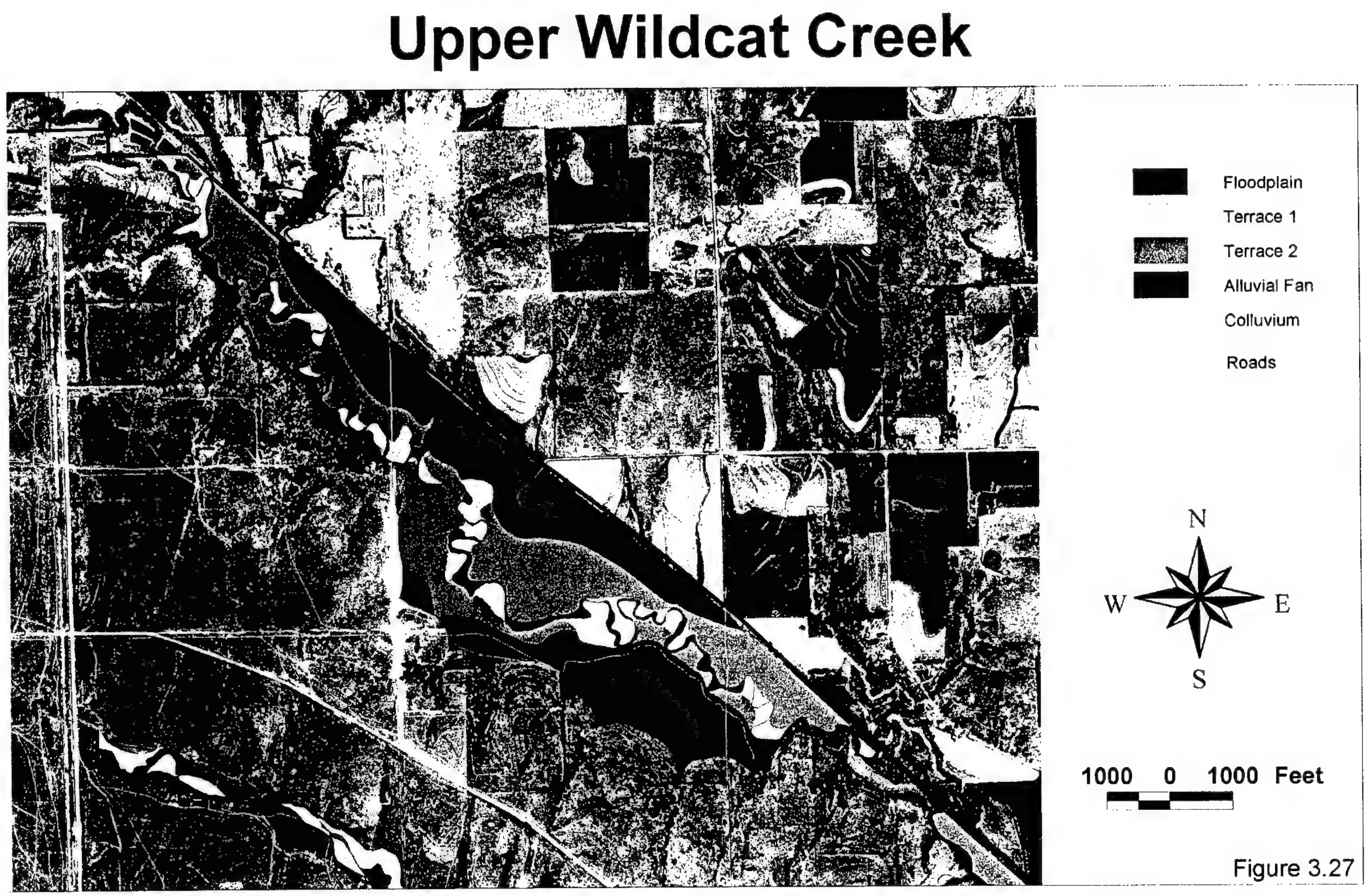


Figure 3.27. Aerial photograph of Upper Wildcat Creek showing color overlays of five different alluvial surfaces.

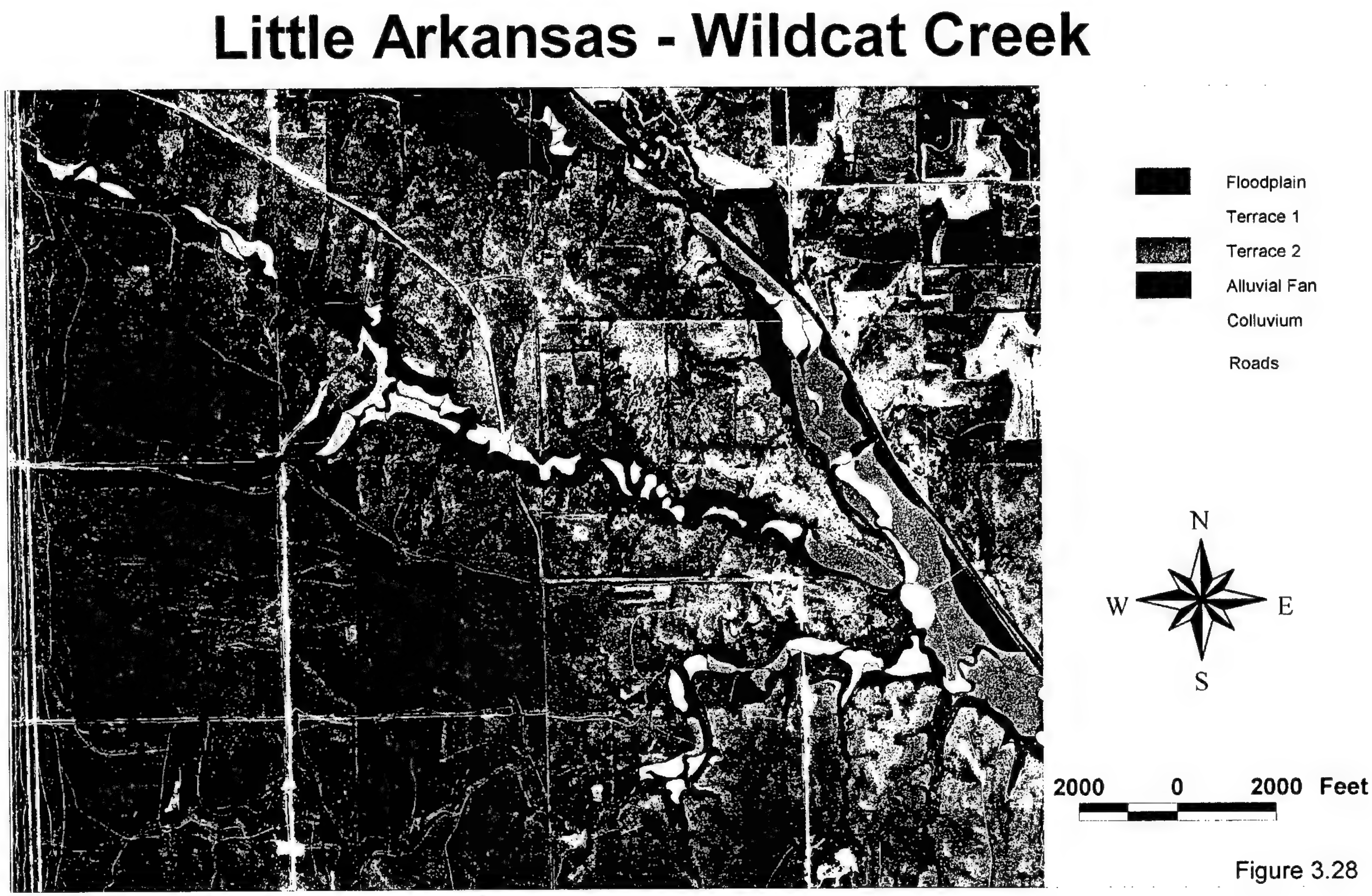


Figure 3.28. Aerial photograph of Little Arkansas/Wildcat Creek confluence, showing color overlays of five different alluvial surfaces.

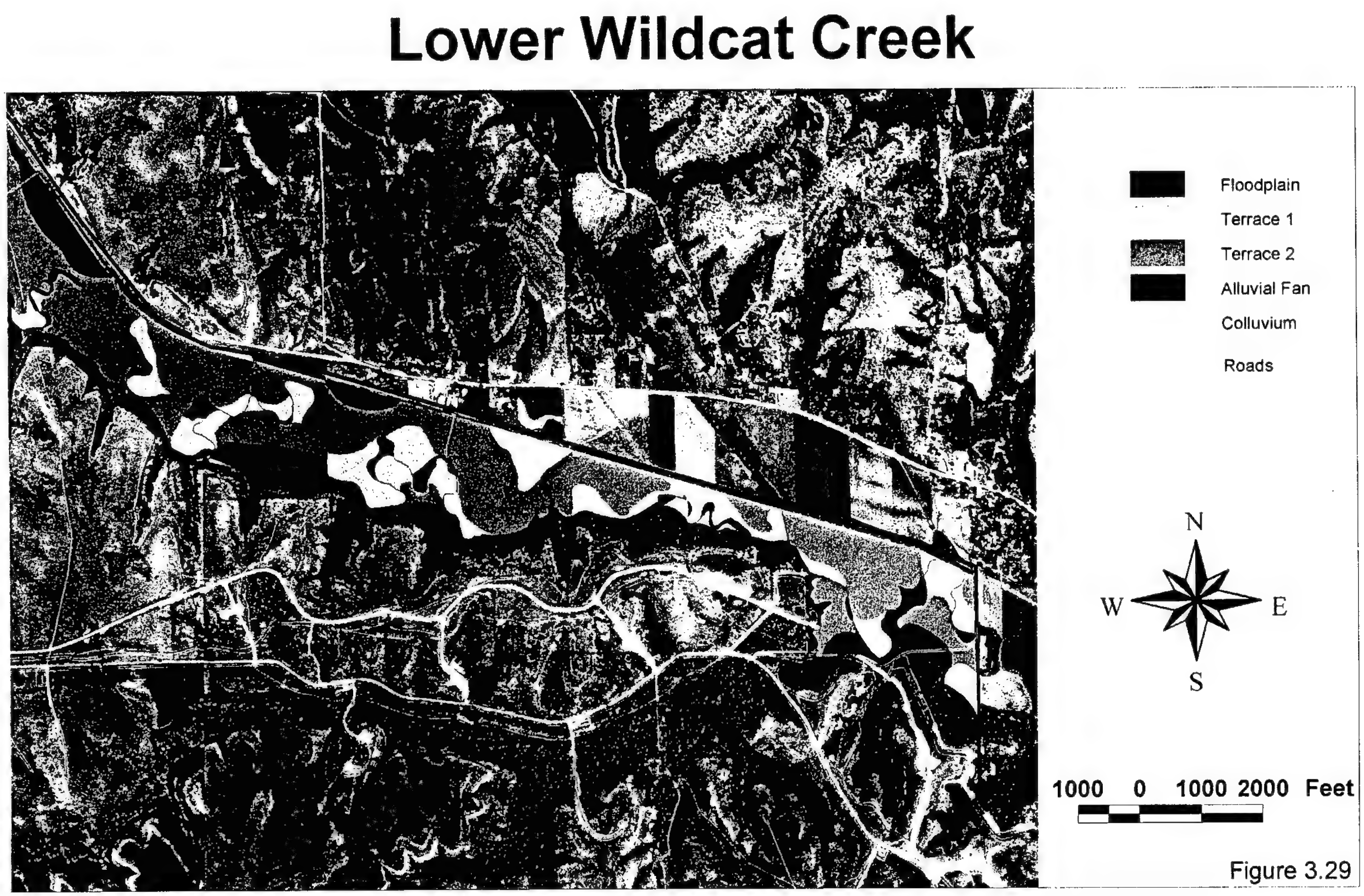
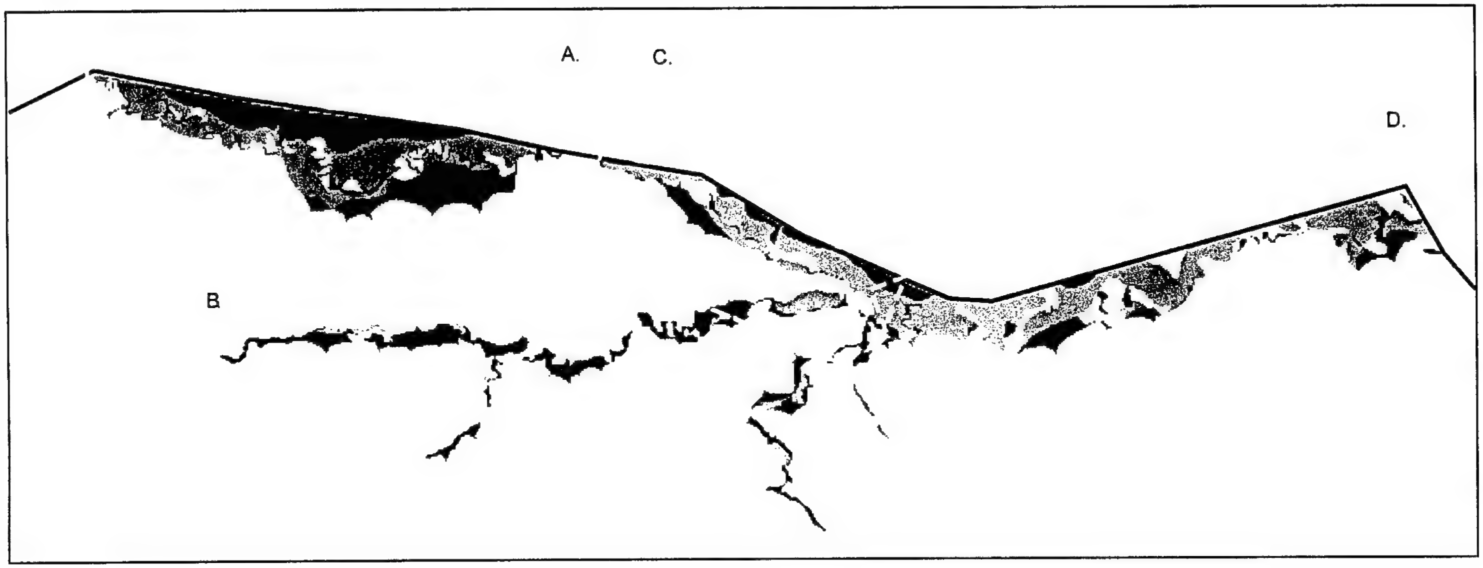


Figure 3.29. Aerial photograph of Lower Wildcat Creek showing color overlays of five different alluvial surfaces.

3-Dimensional Rendering of Wildcat Creek

Index Map



A. Upper

B. Little Arkansas Creek

C. Middle

D. Lower

Figure 3.30

Figure 3.30. Index map for 3-dimensional relief images of Wildcat Creek.

A. Upper Wildcat Creek

B. Little Arkansas Creek

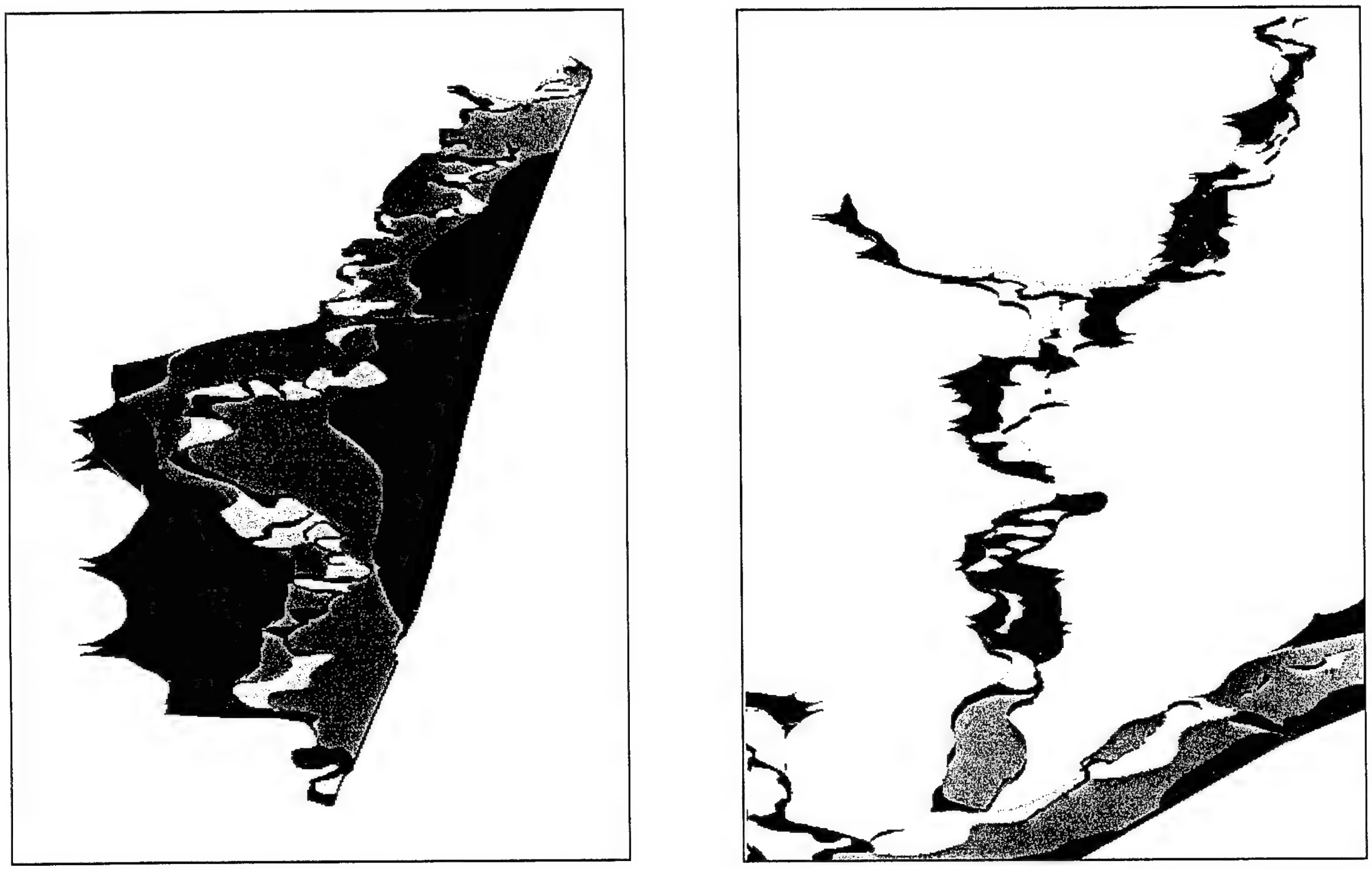


Figure 3.31

Figure 3.31. Oblique relief images for Upper Wildcat Creek and Little Arkansas Creek showing different alluvial fills.

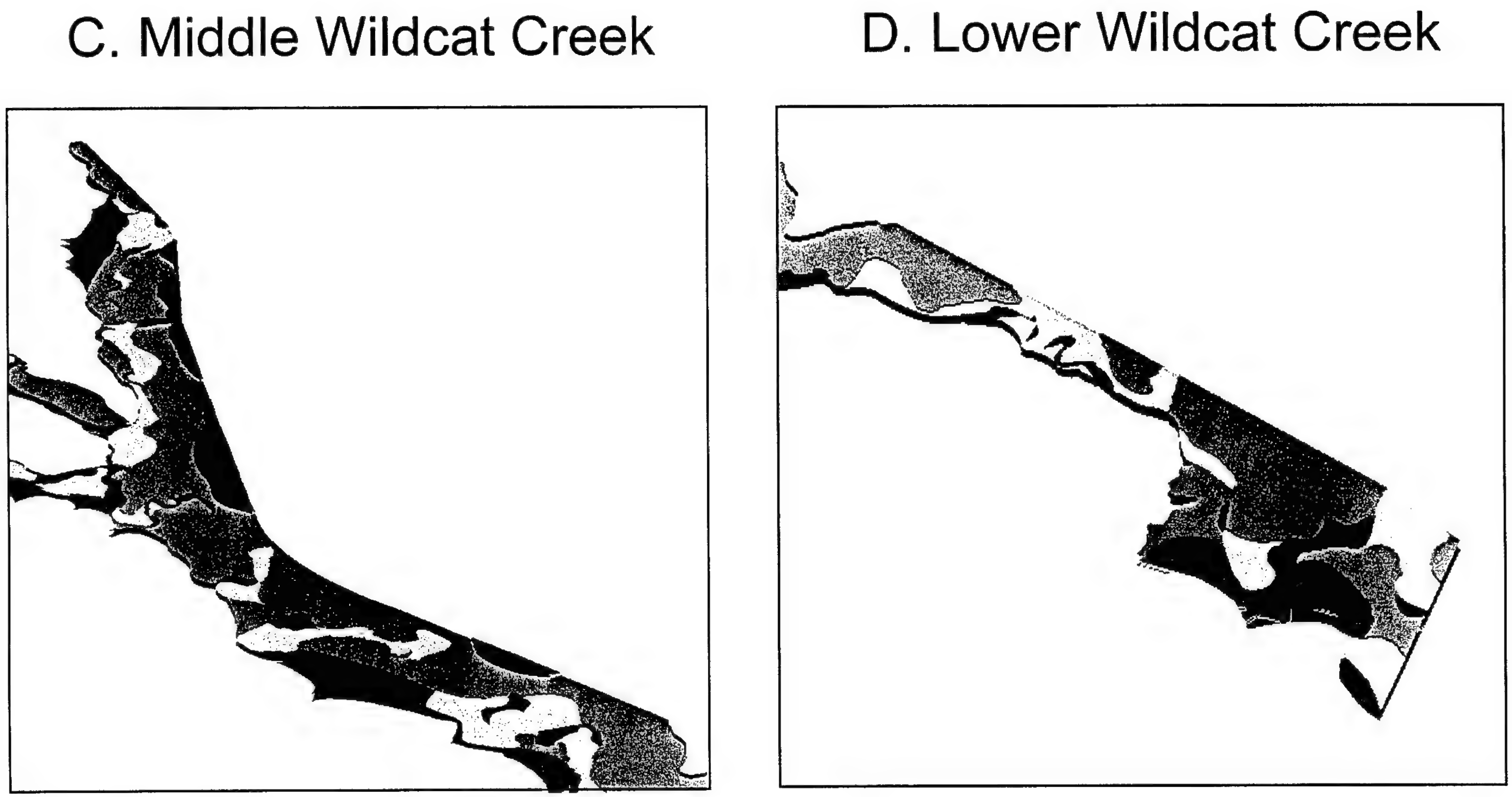


Figure 3.32

Figure 3.32. Oblique relief images for Middle and Lower Wildcat Creek showing different alluvial fills.

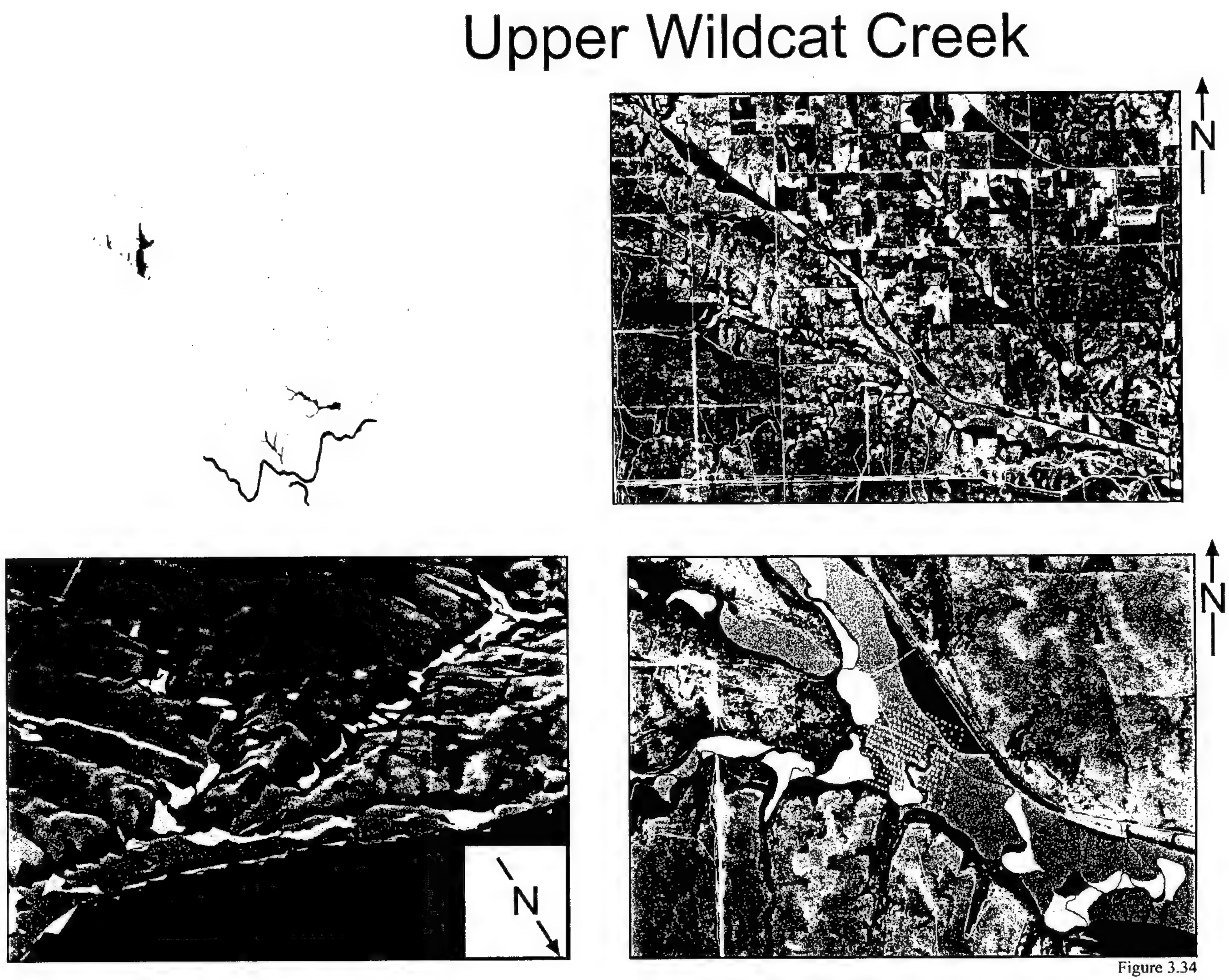


Figure 3.33. High-resolution coring area at Upper Wildcat Creek locality.

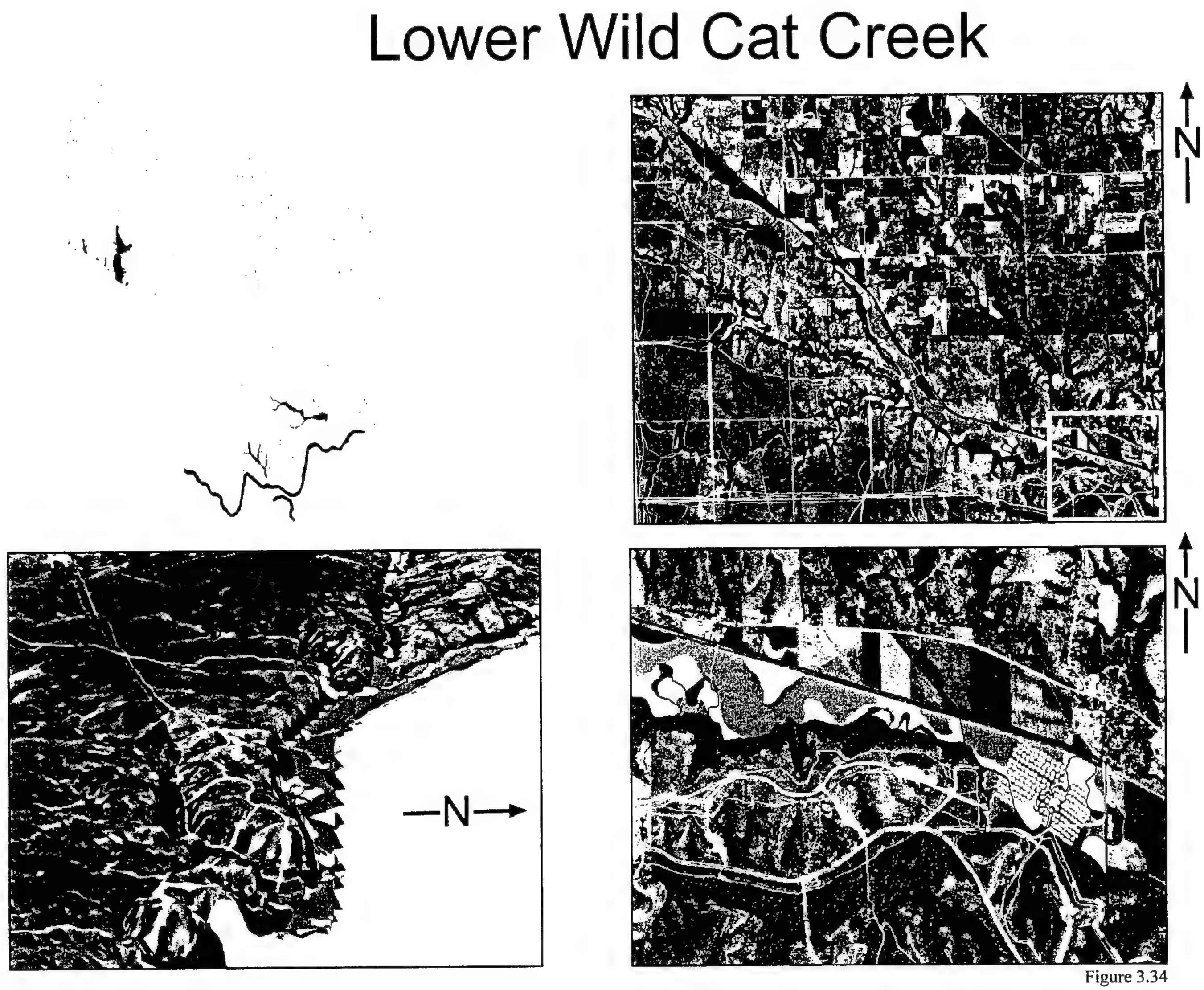


Figure 3.34. High-resolution coring area at Lower Wildcat Creek locality.

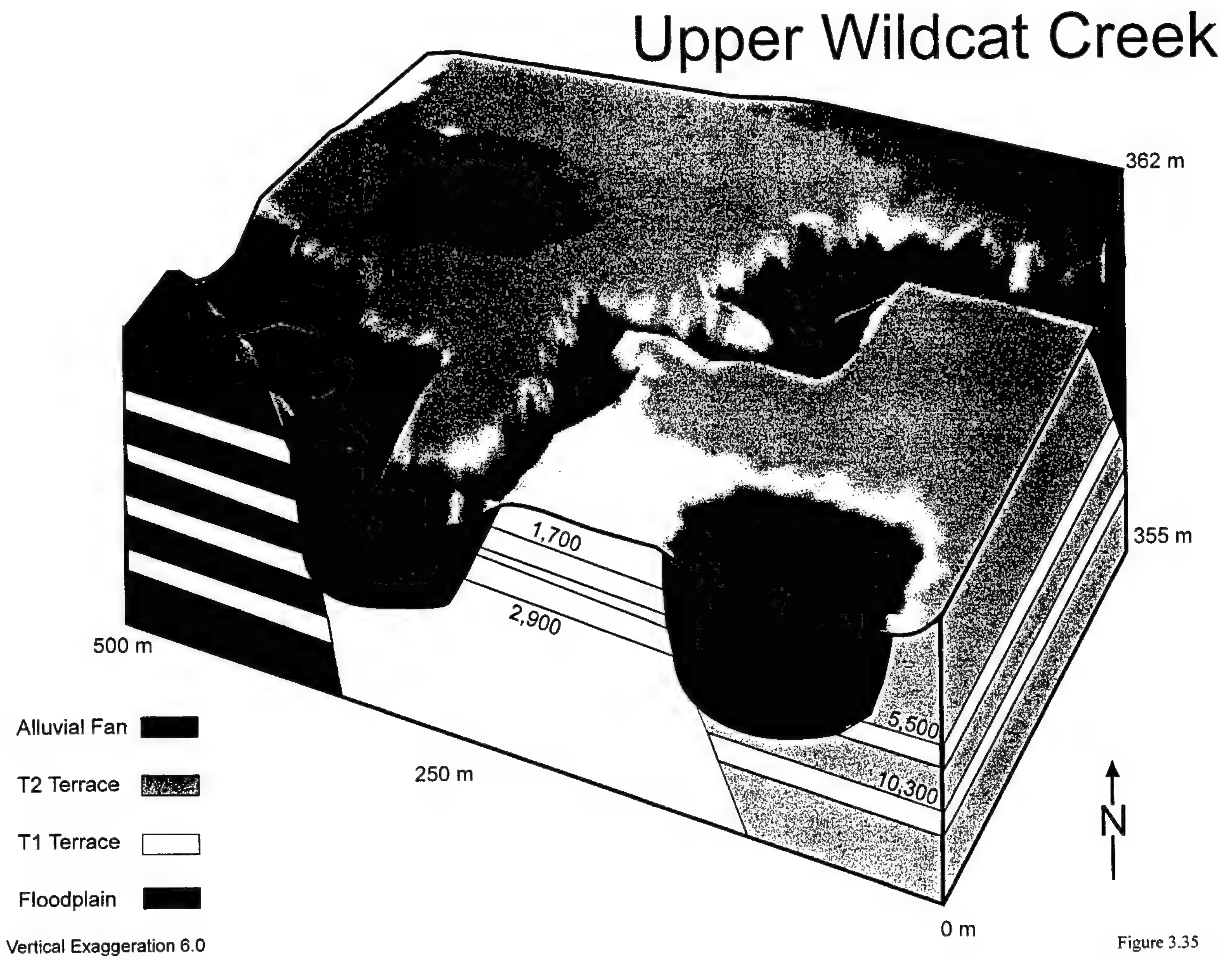


Figure 3.35. 3-dimensional block diagram of Upper Wildcat Creek locality.

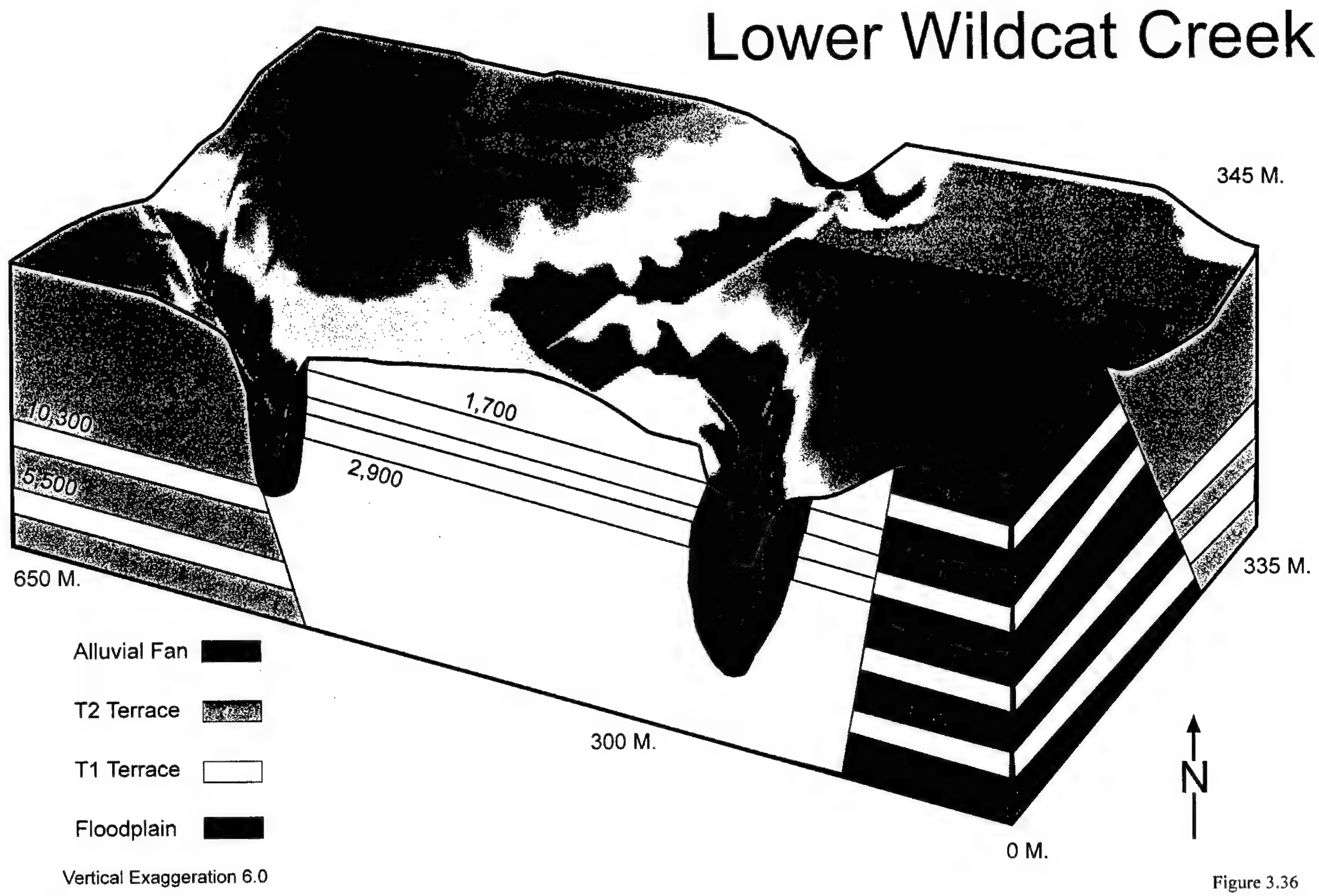


Figure 3.36. 3-dimensional block diagram of Lower Wildcat Creek locality.

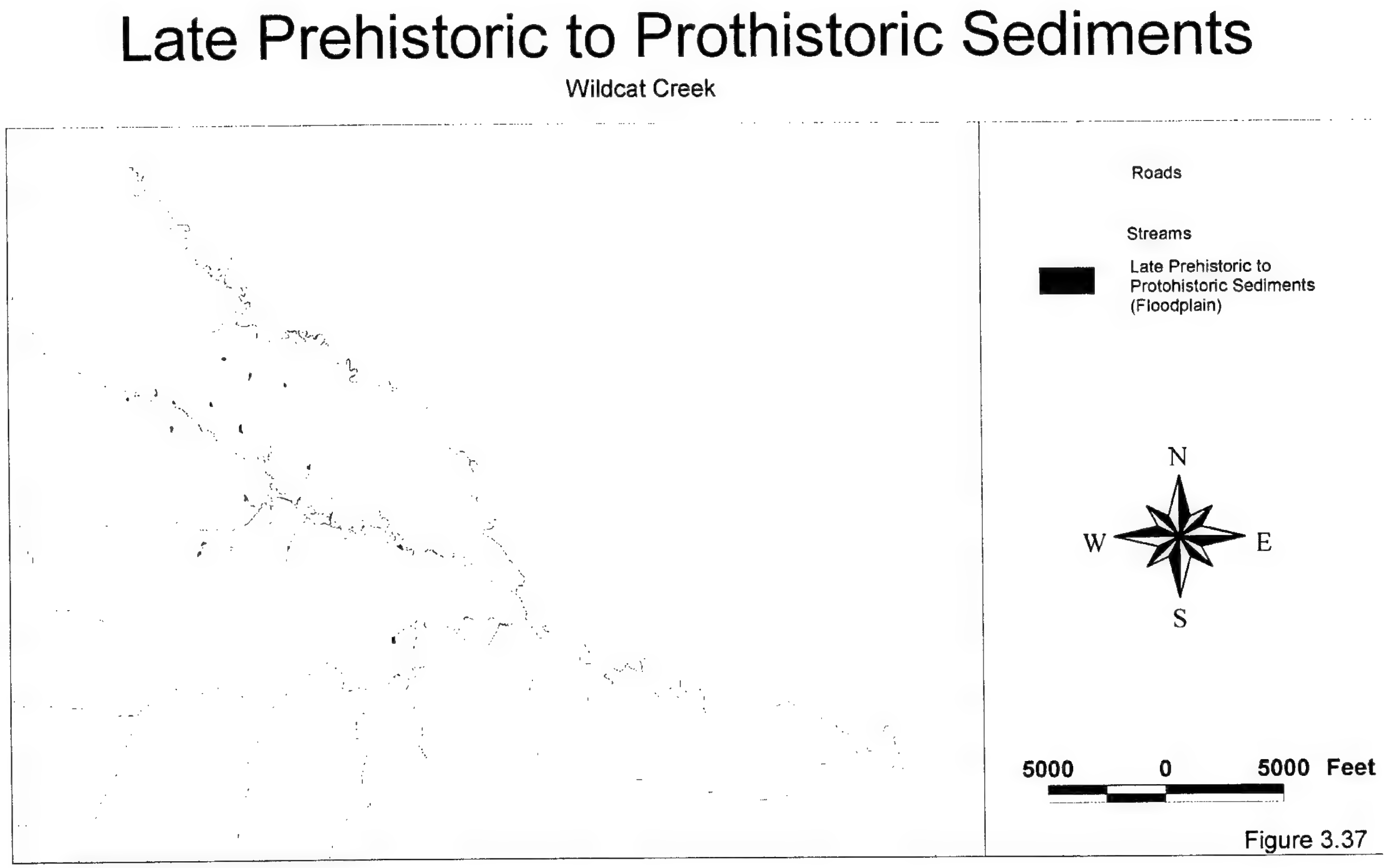


Figure 3.37. Late Prehistoric to Protohistoric sediments along Wildcat Creek.

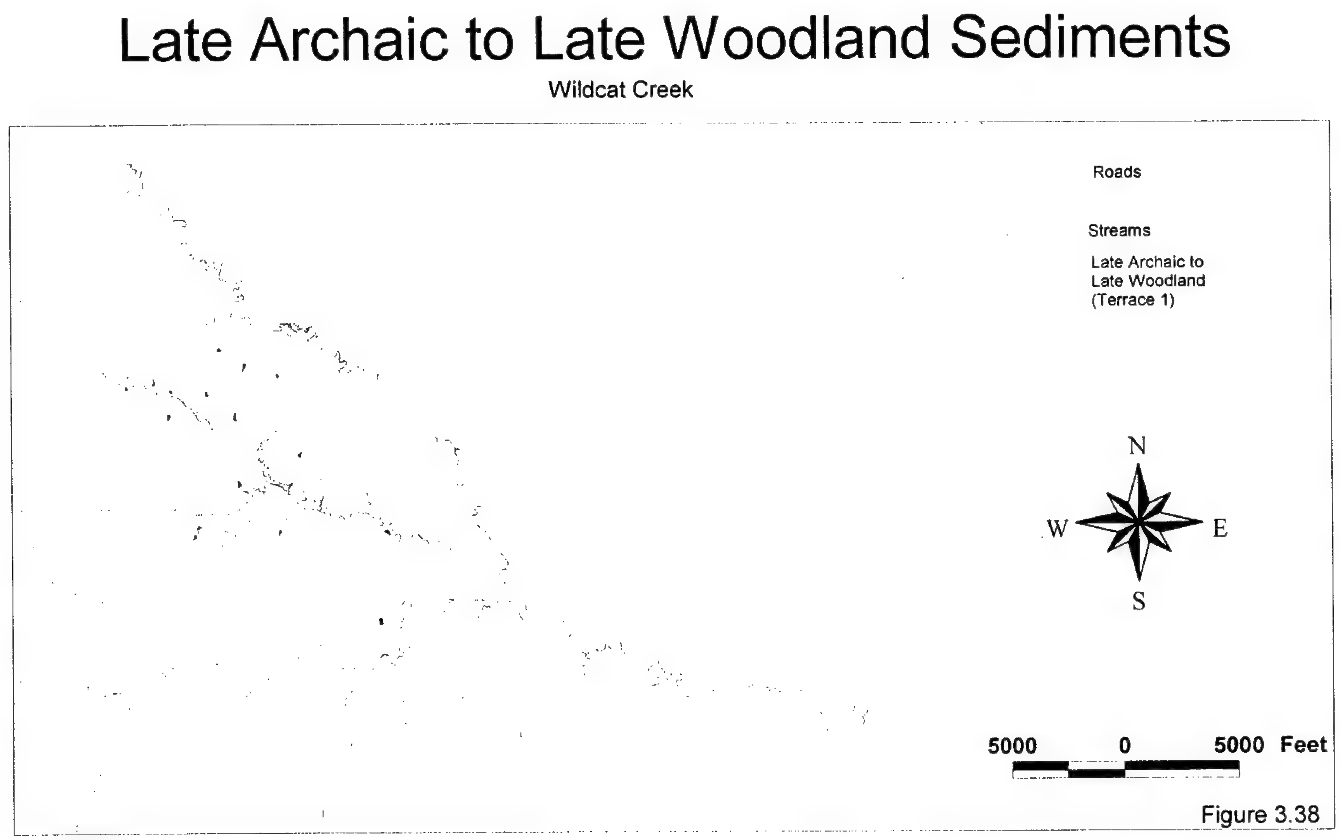


Figure 3.8. Late Archaic to Late Woodland sediments along Wildcat Creek.

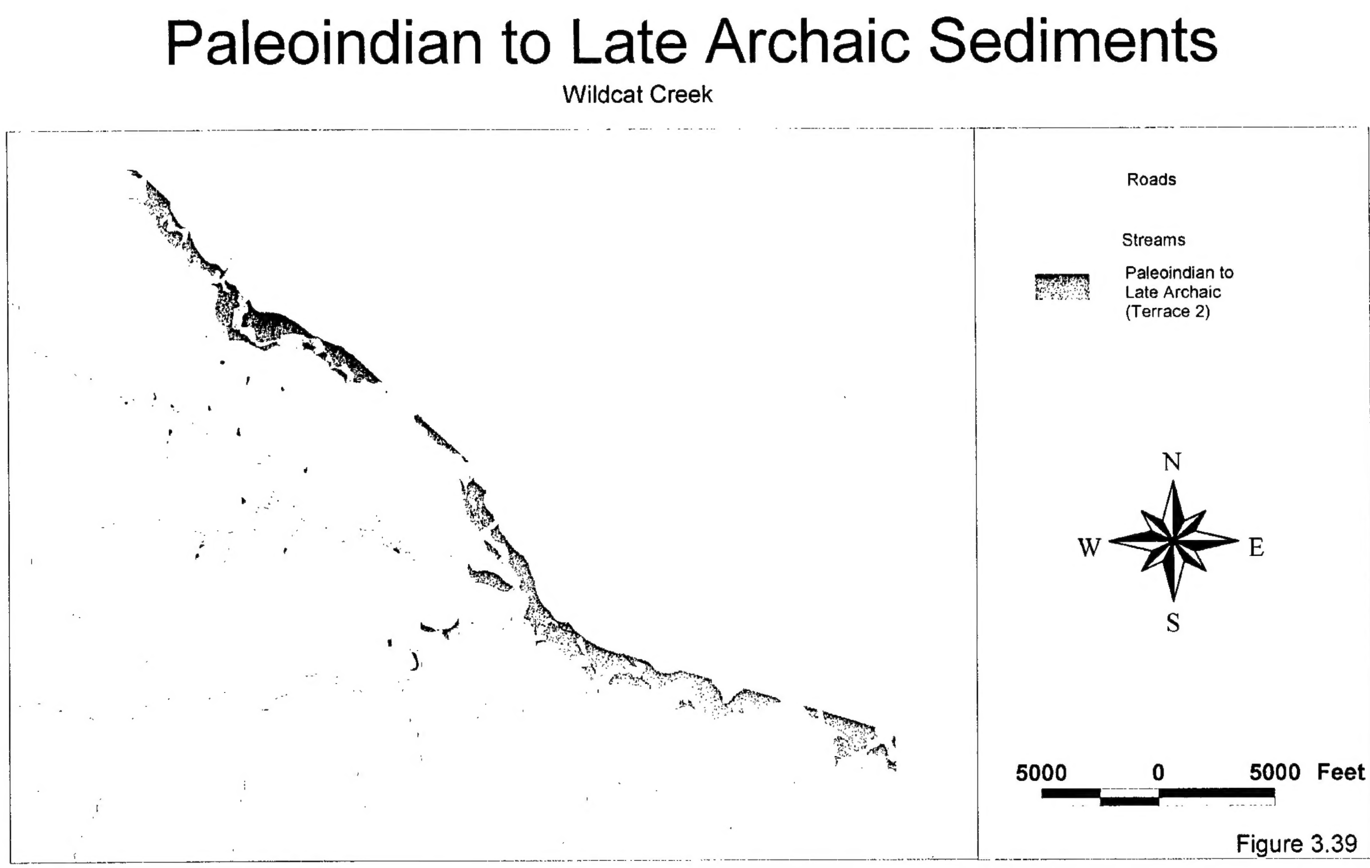


Figure 3.39. Paleoindian to Late Archaic sediments along Wildcat Creek.

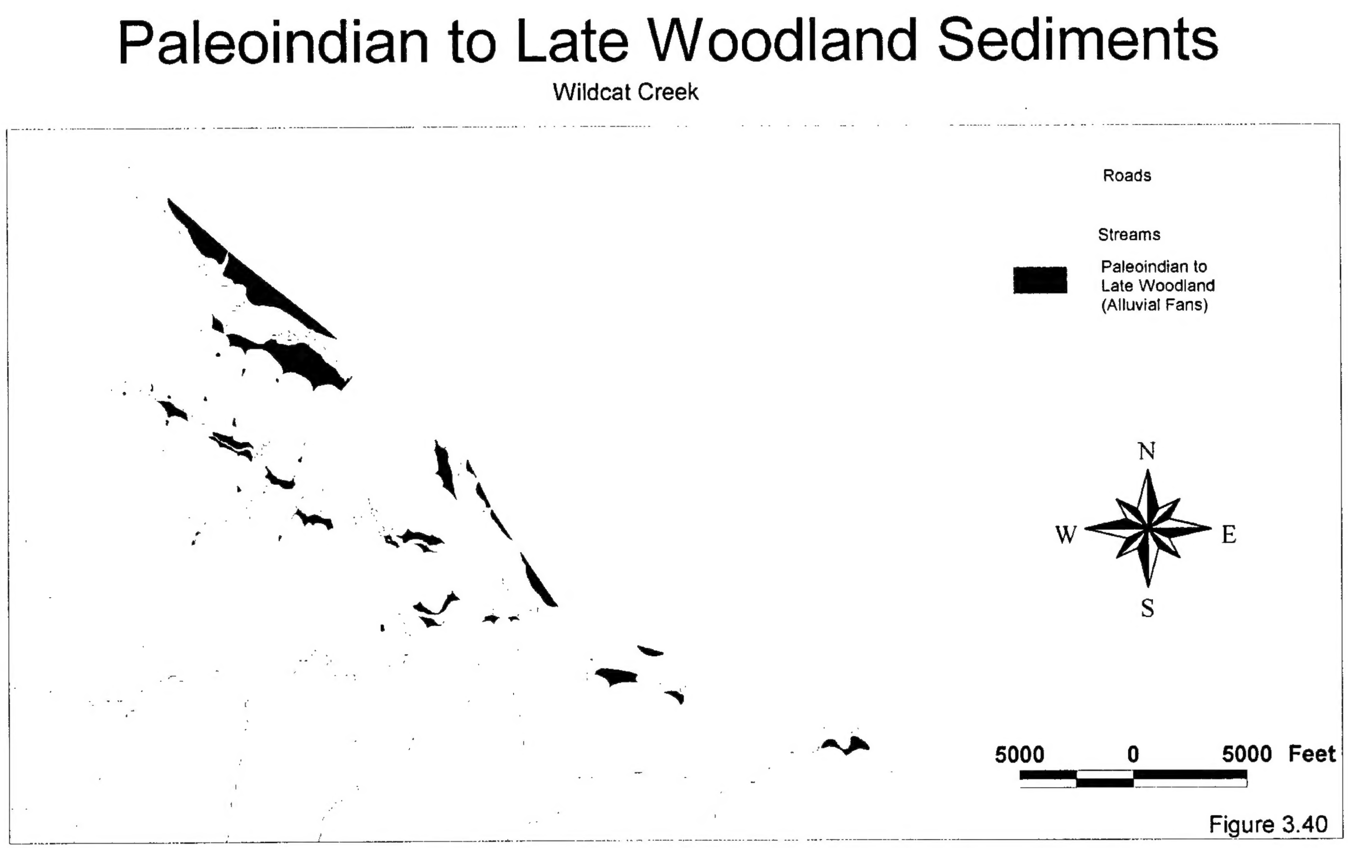


Figure 3.40. Paleoindian to Late Woodland sediments (alluvial fans) along Wildcat Creek.

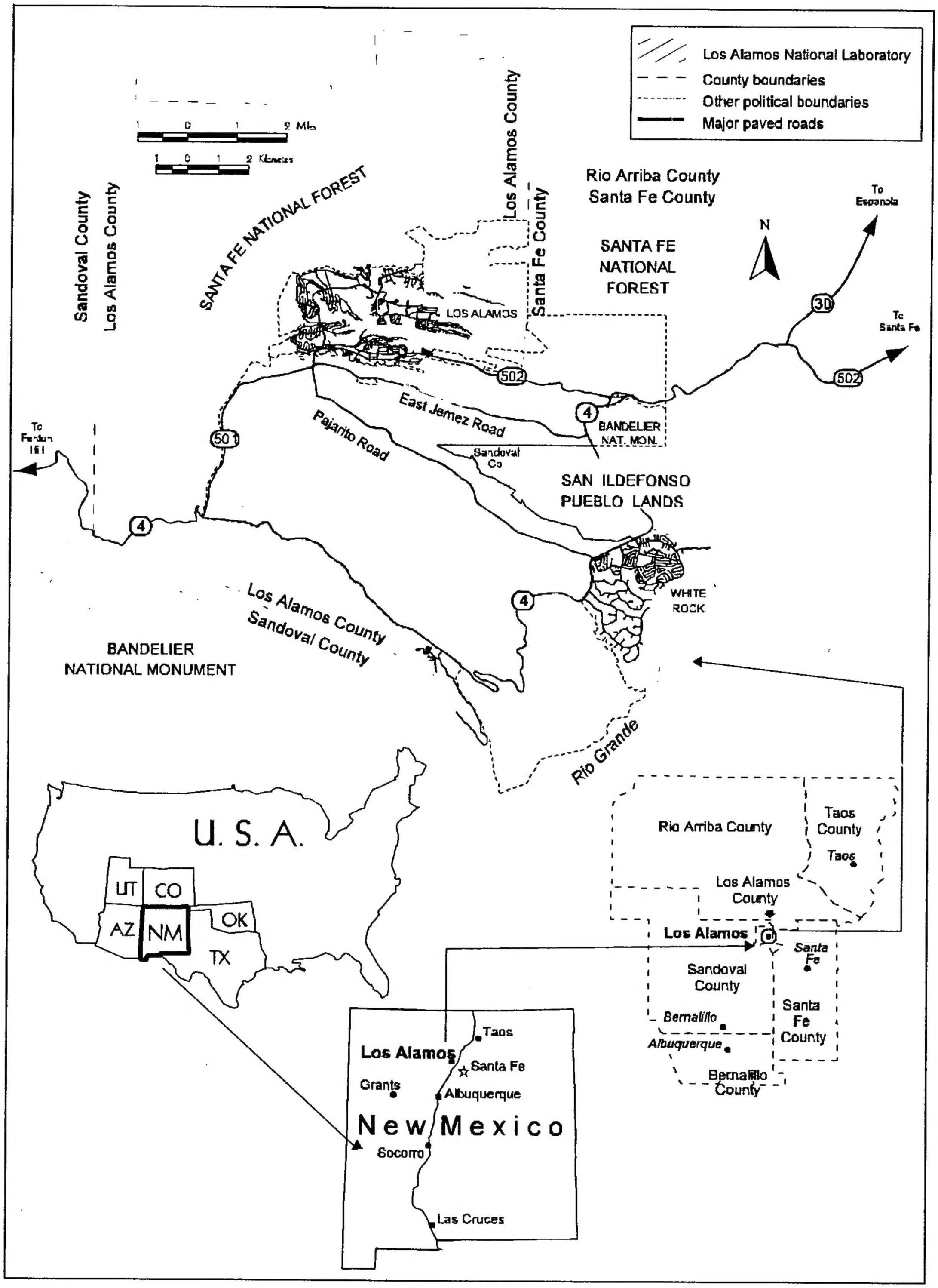


Figure 4.1. Map of Los Alamos National Laboratory in North-Central New Mexico

Figure 4.2 Cerro Grande Fire approaching Los Alamos National Laboratory